NAVORD REPORT 2833

MAGNETIC CONTROL AMPLIFIERS XM-16A AND XM-17A
FOR USE WITH
SERVOMOTORS MARK 7, MARK 8, MARK 14, AND MARK 15

6 MAY 1953

U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

U. S. NAVAL ORDNANCE LABORATORY
White Oak, Silver Spring, Maryland

WB:ETH:fj

21 September 1953

MEMORANDUM

Subj: NavOrd Report 2833, errata sheet for

1. The following is errata sheet for NavOrd Report 2833 by E. T. Hooper.

(1) Page 9, line 1, the word "unstability" should read "instability"

(2) Figure 2, page 20, bottom, the equation

$$\beta = \frac{R}{R + \gamma}$$

should read

$$\beta = \left(\frac{R}{R + \gamma}\right)\left(\frac{\gamma}{R_1}\right)$$

(3) Figure 7, page 25, top, line 3

"bakerlite cores boxes"

should read

"bakelite core boxes"

E. T. Hooper

E. T. Hooper

MAGNETIC CONTROL AMPLIFIERS XM-16A AND XM-17A FOR USE WITH SERVO MOTORS MARK 7, MARK 8, MARK 14, AND MARK 16

Prepared by:

Edward T. Hooper

ABSTRACT: Two magnetic amplifiers are described which are designed to drive a standard line of servo motors. External circuitry permits the adaptation of the basic amplifier to varying servo system requirements. This generally amounts to a compensation for the system bandwidth. This permits the use of the two magnetic control amplifiers in a wide range of applications.

The simple servo design technique employed in determining the external circuitry is outlined. This allows rapid determination of values for compensation of a given system.

The performance of each amplifier-motor combination is given for a large range of gear ratios and with various system loads. These extensive performance curves anticipate the requirements of many systems and can be used to predict the performance of these amplifier-motor combinations in a specified system.

U. S. NAVAL ORDNANCE LABORATORY
White Oak, Silver Spring, Maryland

The Bureau of Ordnance assigned to the Naval Ordnance Laboratory Task NOL-Re8-1-2-53 of which problem 3 was to design, develop, and construct prototypes of packaged magnetic amplifiers for use with servo motors, Mark 7, Mark 8, Mark 14 and Mark 16. The design was to include external circuitry for stabilization and gain in order that the packaged units be as universal in application as possible. The most universally applicable characteristics of standard magnetic amplifiers for use with these motors were to be outlined.

A previous report, "Magnetic Amplifier Servo Compensation," NavOrd Report 2709, by Herbert H. Woodson derived a compensation technique which lent itself very readily to the solution of this problem. Acknowledgement is made by the author to Mr. Woodson for advice and assistance in the completion of this problem.

This report describes amplifier construction details, outlines a simple design procedure for adaptation to servo system requirements, and gives system performance curves for a wide variety of applications.

EDWARD L. WOODYARD
Captain, USN
Commander

D S Muzzey Jr.

D. S. MUZZEY, Jr.
By direction

CONTENTS

ILLUSTRATIONS

MAGNETIC CONTROL AMPLIFIERS XM-16A AND XM-17A FOR USE WITH SERVO MOTORS MARK 7, MARK 8, MARK 14, AND MARK 16

INTRODUCTION

1. The inherently fast speed of response and other advantages of the half-wave magnetic amplifier have been discussed[1]. In addition, the half-wave magnetic amplifier lends itself very readily to the application of compensation techniques[2]. These considerations indicate the use of the half-wave magnetic amplifier with compensation in the solution of many high performance servo problems.

2. A given servo motor may be used in a wide variety of applications. However, regardless of the application, the motor will determine the design of the magnetic amplifier stage which drives it. The entire servo system and the desired performance determine the design of the remainder of the controller.

3. These conditions suggest the possibility of a basic packaged control amplifier in which the output stage is designed for a particular motor while the remainder of the controller can be externally adjusted to meet varying system requirements. This report describes two such controllers, the Magnetic Control Amplifier, XM-16A, for use with the servo motors Mark 7, Mark 8, and Mark 16 and the Magnetic Control Amplifier XM-17A for use with the servo motor Mark 14.[3] This report is based on Modification 0 of these motors and is thereby applicable to all modifications having the same electrical characteristics.

SERVO DESIGN

4. The servo motors, Mark 7, Mark 8, Mark 16, and Mark 14 each have a frequency response characteristic as shown qualitatively by curve a, figure 1. They have a steady state sinusoidal transfer function of the type[4]

$$G = \frac{K}{T_m j\omega (T_m j\omega + 1)} \quad \text{Eq. (1)}$$

The motor has a frequency corner ω_1, seen in figure 1 equal to $1/T_m$ and occurring at a phase shift of 45 degrees. When this motor is placed in a closed loop system where the load

friction and inertia reflected to the motor shaft is negligible, as in an instrument type servo, a resultant bandwidth of approximately the same frequency as the motor corner (ω_1) is obtained. For a first order closed loop system the bandwidth is defined as the frequency at the 90° phase shift point. Addition of appreciable frictional loading to the system will increase the bandwidth while inertia loading will reduce the bandwidth. Under these conditions the new system bandwidth is used as a basis for controller design. Compensating for this system time constant results in improved performance. In the following discussion this compensation is accomplished within the magnetic amplifier.

5. By cascading a lead network having the characteristics of curve b, figure 1 (lower break frequency, ω_2, and upper break frequency, ω_3) with the motor having the characteristics of curve a, the system break frequency is increased as shown by curve c. This permits increased gain to be stabilized in a closed loop, resulting in improvement in velocity constant and static accuracy.

6. The necessary lead function for extension of the system break frequency is provided by a three stage magnetic amplifier with negative integral feedback around it. Figure 2 is a block diagram of this lead network. If R_1 is made equal to zero, then the entire output of the amplifier is fed into the integrating network, and γ equals zero. Under this condition, the transfer function of the system is

$$\frac{E_o}{E_i} = \frac{\frac{K}{1 + \alpha K}(\alpha T j\omega + 1)}{\frac{1}{1 + \alpha K}\alpha T j\omega + 1} \qquad \text{Eq. (2)}$$

with a lower break frequency (ω_2 in figure 1) equal to $1/\alpha T$, a break frequency spread (ω_3/ω_2 in figure 1) equal to $1 + \alpha K$, and zero frequency gain, $K/(1 + \alpha K)$.[2] The value of α is given in figure 2.

7. When it is necessary to feed less than the entire output of the amplifier into the integrating network. R_1 is made greater than zero. In addition to dividing the output of the amplifier, this influences the RC network so that the transfer function of the system becomes

$$\frac{E_o}{E_i} = \frac{\frac{K}{1 + \alpha'\beta K}(\alpha' T j\omega + 1)}{\frac{1}{1 + \alpha'\beta K}\alpha' T j\omega + 1} \qquad \text{Eq. (3)}$$

with a lower break frequency equal to $1/(\alpha' T)$, break frequency spread, $1 + \alpha' \beta K$, and zero frequency gain $K/(1 + \alpha' \beta K)$. The values for α' and β are given in figure 2.

8. As can be seen from the above, the corner frequency extension is a function of the d-c gain, K, of the three stage magnetic amplifier around which the negative integral feedback is placed. This gain should be large for a considerable extension of the corner.

9. When the system bandwidth is initially low, a large extension is possible. Thus with 400 cycle line frequency an uncompensated system bandwidth of 2 radians per second can be extended to 60 radians per second, a factor of 30. When the bandwidth is initially high, less extension is allowable. Thus with 400 cycle line frequency a bandwidth of 25 radians per second possibly can be extended only by a factor of 5, or to 125 radians per second. This limitation is due to amplifier phase shift contributing to lead circuit instability at the higher frequencies.

10. To achieve a desirable degree of compensation, a lower break frequency, ω_2, figure 1, of approximately twice the system bandwidth, ω_1, is indicated where the uncompensated system bandwidth is relatively high. With a low uncompensated system bandwidth, the lower break frequency of the lead network may be set up by a higher factor. Figure 3 is a plot of this factor, ω_2/ω_1, for various system bandwidths. This is an approximation of a desirable lower break frequency and can be varied quite widely. As is seen from figure 3, in systems with very low corner frequencies, ω_2/ω_1 can be high. This is a result of the greater allowable break frequency spread ω_3/ω_2, in systems with low corner frequencies. A wide break frequency spread results in greater amplitude of the lead network phase curve b, figure 1. This permits phase curve b to be moved out farther in the frequency spectrum without the compensated phase curve c, figure 1, falling below a 45 degree phase margin. Although the ω_2/ω_1 ratio designated in figure 3 is satisfactory over a nominal range of gear ratios, it has been found advisable at high gear ratios to lower this ratio slightly. Here the break frequency spread, ω_3/ω_2, is reduced due to the loss in d-c gain of the amplifier at high gear ratios where the value of R_a (figure 2) is small. The reduced break frequency spread means less amplitude to the phase shift curve b, figure 1, which necessitates moving the phase curve b down in the frequency spectrum to ensure a 45 degree phase margin.

11. Having chosen the desired lower break frequency, it can be realized by the proper choice of component values as shown

in figure 2. Assume for the moment $R_1 = 0$. The lower break frequency is then $1/(\alpha RC)$, where $\alpha = R_c/(R_c + R)$. If the signal source is a control transformer, it is desirable to maintain a value of R_c, figure 2, of at least 10,000 ohms. This with the chosen values of R and C determines the lower break frequency. If maintaining $R_1 = 0$ results in too much feedback, the lead network will be unstable at the higher frequencies due to amplifier phase shift. To eliminate this the output of the amplifier is divided down by increasing R_1 and decreasing R_2. This decreases the feedback but also changes the lower break frequency which is now $1/(\alpha' RC)$ where

$$\alpha' = \alpha \left[\frac{1 + \frac{\gamma}{R}}{1 + \frac{\gamma}{R+R_c}} \right] \quad \text{and} \quad \gamma = \frac{R_1 R_2}{R_1 + R_2} .$$

12. The above discussion leads to a very simple design procedure having the following steps:

(1) Determine the approximate uncompensated system bandwidth. This can be done by making a frequency response analysis of an uncompensated closed loop with the amplifier gain attenuated to give the desired damping*. Or this can be determined by open loop measurements outlined in many servo texts.

(2) Employ a lead network of the type discussed. The lower break frequency can be chosen from figure 3, if desired, knowing the bandwidth obtained in (1). The component values to give the desired lower break frequency can be calculated from the equations given in the text and in figure 2.

(3) The break frequency spread need not be determined. If this is too large, the feedback loop will be unstable in which case the value of R_1 must be increased and R_2 decreased to lower the loop gain.

(4) Adjust gain. It is apparent that a given compensation system has an upper limit of gain which it can stabilize. Excessive gain must be attenuated by some means. In figure 2, the resistance R_a is used for this purpose.

13. A three stage magnetic amplifier designed for a particular motor and employing lead compensation as above can be so constructed that no changes must be made in the amplifier proper for operation over a wide range of gear ratios and load conditions. This is accomplished by placing the feedback

*The instrument used in frequency response analysis for this report was a simplified version of that described in reference 5.

network components and attenuating resistance R_a external to the amplifier proper where they may be adjusted for varying system requirements. The resultant magnetic control amplifier is very flexible and wide in its application.

14. In addition, the access to the amplifier provided by the above design permits ready use of other types of compensation such as lag compensation and integration. These techniques have been applied to half-wave magnetic amplifiers.[2] A combination of lead-lag compensation is also feasible. These possibilities further indicate the flexibility of the basic magnetic amplifier employing external network components.

MAGNETIC CONTROL AMPLIFIER XM-16A

15. The design of the magnetic amplifier is determined by the demands of the motor and general system specifications. The power requirements of the motor dictate the design of the output stage. The servo motors, Mark 8 and Mark 16, operated with series control phase windings, and the servo motor Mark 7, operated with parallel control phase windings, demand amplifier output power of relatively the same value. This is close enough to permit the use of the same output stage with all three motors. The Mark 12 servo motor, not covered in this report, may also be driven by this amplifier as the Mark 12 motor is the Mark 7 servo motor with tachometer generator added. The remainder of the magnetic amplifier is determined by the gain required to satisfy the system specifications. In the Magnetic Control Amplifier XM-16A, two additional stages are sufficient to supply the necessary gain. The basic amplifier consists therefore of three half-wave bridge stages. The negative integral feedback described in the Servo Design section of this report is placed around these three stages, giving a lead characteristic to the amplifier.

16. The delay has been minimized in the half-wave magnetic amplifier.[1] This is one cycle of the power frequency for one stage and an additional half cycle delay for each additional stage. Thus the three stages of the Magnetic Control Amplifier XM-16A introduce a delay of, at worst, two cycles of the 400 cycle per second supply. This is a delay of 5 milliseconds.

17. The d-c component in the output of the amplifier is of interest in computing the break frequency spread. This d-c component, which is applied to the integrating network, varies with values of R_a, figure 2. This is due to the changing load condition on the amplifier. With $R_a = 0$ the amplifier

feeds a very inductive load, while an increased value of R_a makes the load on the amplifier appear less inductive. These d-c gain curves for various values of R_a are shown in figure 4. This is the gain K of figure 2.

18. When driving a two phase 400 cycle servo motor, the 400 cycle component in the output of the amplifier likewise is of interest. This component measured at the output of the amplifier is also seen to vary slightly and inversely with values of R_a. These a-c gain curves are shown in figure 5. This amount of output is satisfactory in the type of application discussed here. Where full motor output torque is needed, a slightly larger unit is required. In the plotting of the curves of both figure 4 and figure 5, the motor load was a Mark 8 servo motor with control phase windings in series.

19. The circuit diagram applicable to both Magnetic Control Amplifier XM-16A and Magnetic Control Amplifier XM-17A is shown in figure 6. The values of components for the XM-16A are given in Table I.

20. The first stage of the amplifier employs two cores, one supplied with windings W_1, W_2, W_3, the other core supplied with windings W_4, W_5, W_6, (see figure 6). Thus, when one core saturates, diagonally opposite legs of the bridge are reduced to a low impedance. The bridge is completed with selenium rectifiers, Rx_1 and Rx_2. These are doubler connected with the output of the bridge taken from across the center lugs of these rectifiers. The second stage likewise is composed of two cores, one supplied with windings W_7, W_8, W_9, the other windings W_{10}, W_{11}, W_{12}, with rectifiers Rx_3 and Rx_4. The third stage cores are supplied with windings W_{13}, W_{14}, W_{15}, and W_{16}, W_{17}, W_{18}, respectively. The core dimensions are given in figure 7.

21. The cores are reset to the flux level which gives the proper firing angle by the reset voltage across the portion of the power winding below the tap as shown in figure 6. This is 450 turns in the first two stages and 400 turns in the third stage. R_{X_7} is the doubler connected rectifier for supplying the reset voltage. The resistors in the reset circuits are adjusted to give the proper reset voltage. In general, the firing angles are set at approximately 150° of the conduction half cycle.

22. The cable connections to the amplifier are made through an octal plug whose numbered pins appear at the left side of figure 6. Identification of the pin numbers is found in Table I. The external components plug into a Winchester socket

as shown at the bottom of figure 6. Circuit diagrams of the external components used both with lead compensation and without lead compensation are shown in figure 8.

23. The final packaged unit minus external feedback network components is 3" x 2 1/2" x 2 3/8", occupying 18 cubic inches and weighing 15 ounces. A photograph of the Magnetic Control Amplifier XM-16A, without external feedback network components is shown in figure 9.

MAGNETIC CONTROL AMPLIFIER XM-17A

24. This amplifier is designed to drive the servo motor Mark 14, with its control phase windings in parallel. This motor demands less power output from the amplifier than the motors operating from Magnetic Control Amplifier XM-16A. This permits a reduction in size of the output stage and thereby an over-all reduction in amplifier size. Apart from this change the basic amplifier is essentially the same as the XM-16A.

25. Again two stages in addition to the output stage are sufficient for the gain requirements. The negative integral feedback described in the Servo Design section of this report is placed around the three stages of amplification giving a lead characteristic to the amplifier.

26. The three stages of the Magnetic Control Amplifier XM-17A introduce, at worst, a delay of two cycles of the 400 cycle per second supply.[1] This is a delay of 5 milliseconds. The d-c component in the output of the amplifier, which is of interest in computing the break frequency spread, is shown in figure 10. This is a plot of the gain K of figure 2. Again it is seen to vary with R_a (figure 2) due to the change in load condition of the amplifier.

27. The a-c component in the amplifier output which is useful for driving the two phase 400 cycle servo motor is shown in figure 11. This gain curve varies slightly with values of R_a. The curves of figures 10 and 11 were taken with a motor load on the amplifier consisting of the Mark 14 servo motor with control phase windings in parallel.

28. The schematic representation in figure 6 applies to Magnetic Control Amplifier XM-17A, while values of components for this amplifier are given in Table II.

29. The first stage is composed of two cores, one supplied with windings W_1, W_2, W_3 and the other windings W_4, W_5, W_6. The

bridge is completed with selenium rectifiers, R_{X1} and R_{X2}. These are doubler connected with the output of the bridge taken from the center lugs of these rectifiers. The two cores of the second stage are supplied with windings W_7, W_8, W_9 and W_{10}, W_{11}, W_{12}, respectively, and used in conjunction with rectifiers R_{X3} and R_{X4}. The third stage cores are supplied with windings W_{13}, W_{14}, W_{15}, and W_{16}, W_{17}, W_{18}, respectively. The core dimensions are given in figure 7.

30. The cores are reset to the flux level which gives the proper firing angle by the reset voltage applied across the portion of the power winding below the tap as shown in figure 6. This is 450 turns in all three stages. R_{X7} is the doubler connected rectifier for supplying the reset voltages. The resistors in the reset circuits are adjusted to give the desired reset voltage which in general is for a firing angle of approximately 150° of the conducting half cycle.

31. The cable connections to the amplifier are made through an octal plug whose numbered pins appear at the left side of figure 6. Identification of the pin numbers is found in Table II. The external components plug into a Winchester socket as shown at the bottom of figure 6. Circuit diagrams of the external components used both with lead compensation and without lead compensation are shown in figure 8. The final packaged unit minus external feedback network components is 2 3/4" x 2 3/8" x 2 3/16", occupying 14.5 cubic inches and weighing 11.5 ounces. A photograph of the Magnetic Control Amplifier XM-17A without external feedback network components is shown in figure 12.

PERFORMANCE OF MAGNETIC CONTROL AMPLIFIER XM-16A WITH THE MARK 7 SERVO MOTOR

A. With No Added Inertia.

32. The Mark 7 servo motor has a corner frequency, ω_1, of approximately 27 radians per second. This was found by making a frequency analysis of an uncompensated closed loop system involving the Mark 7 motor with no added friction or inertia. The control phase windings of the motor were in parallel. The fixed phase winding was operated in series with a 0.2 µf capacitor.

33. In accordance with the servo design technique previously discussed, the lower break frequency of the lead network was set at 47 radians per second. The voltage taken from the divider, composed of R_1 and R_2, figure 2, was reduced until

there was no lead circuit unstability due to excessive gain around the feedback loop. The attenuating resistance, R_a, was adjusted for the desired resonant rise of the system. In all the systems for which data is presented in this report the resonant rise was set at 2.28 db which is a phase margin of 45 degrees.

34. The compensated system was evaluated over a range of gear ratios. At gear ratios of 385:1 and higher from the motor to the control transformer, it was found desirable to reduce the lower break frequency. This is due to the lowering of the value of R_a at high gear ratios which decreases the dc gain of the amplifier. (See figure 4). This loss in dc gain reduces the break frequency spread and lowers the amplitude of the phase shift curve b, figure 1. This in turn necessitates the bringing of the phase shift curve b, figure 1, down in the frequency spectrum to maintain a 45 degree phase margin or in other words decrease the lower break frequency.

35. The values of the feedback network components for each gear ratio at which the system was evaluated are given in Table III. Also shown is the lower break frequency, ω_2, as set for each gear ratio and the ratio, ω_2/ω_1. It should be noted that the network values given were chosen to illustrate the procedure and performance and represent only one possible combination of these values. Other combinations within the restrictions given by the equations of figure 2, will produce the same performance or some desired variation in performance, such as increased bandwidth with less damping.

36. For the network values given in Table III the performance of the compensated system with the Mark 7 motor and no added inertia is shown in figure 13. Curve a, figure 13, shows the bandwidth extension over the uncompensated bandwidth of 27 radians per second. Curve b, figure 13, shows the static error in degrees and curve c, figure 13, shows the velocity constant in degrees per second of angular velocity at the control transformer per degree error signal. The velocity constant is somewhat low due to the d-c component of voltage applied to the motor. The velocity constant may be raised if necessary by applying lag compensation techniques.

B - With Added Inertia.

37. In order to present a more complete picture of the operation of Magnetic Control Amplifier XM-16A with the Mark 7 servo motor it was desired to give the performance under different load conditions. To this end inertia loads were added to the system.

38. The moment of inertia of the Mark 7, servo motor is 0.0167 in^2 oz. This moment of inertia is denoted by J_{m7} and is the total moment of inertia in systems using the Mark 7 motor with no added inertia, where gear train inertia can be neglected. To this system was added a moment of inertia equal to 4.23 times the motor inertia, J_{m7}. This made a total moment of inertia equal to 5.23 J_{m7}. Under this load condition the uncompensated system bandwidth, ω_1 of figure 1, was lowered to 5.4 radians per second.

39. The lower break frequency of the lead network was set at 22.5 radians per second for the lower range of gear ratios and reduced somewhat at higher ranges. The network values for this load condition are given in Table IV and the performance of the system at various gear ratios given in figure 14. Here the bandwidth is seen to be extended from 5.4 radians per second to 90 radians per second at a gear ratio of 19.25:1. This is a larger extension factor than achieved in the system with no added inertia.

40. To present another load condition, which incidentally represents a more difficult damping problem, more inertia was added to the system. A moment of inertia of 13.3 times the motor inertia J_{m7}, was added to the system making a total moment of inertia equal to 14.3 J_{m7}. Under this load condition the uncompensated system bandwidth was lowered to 1.9 radians per second. Upon applying compensation the performance curves of figure 15 were obtained using the network component values given in Table V. Here the 1.9 radians per second bandwidth was extended to 60 radians per second at a gear ratio of 19.25. This is an extension of a factor of 31.6.

41. The addition of a frictional load to the system would extend the bandwidth and present the designer with a less acute damping problem. Since such a system demands increased amplifier gain and motor output torque rather than bandwidth extension it was felt that discussion of this type of load was beyond the scope of this paper.

42. The Magnetic Control Amplifier XM-16A is therefore shown to be applicable for operation with the Mark 7 servo motor under a variety of load conditions and over a range of gear ratios from 19.25 to 1155. At gear ratios higher than this the basic amplifier can still be used without compensation, employing external circuit connections of figure 8 (b), although the gain limitation of the amplifier is approached.

PERFORMANCE OF MAGNETIC CONTROL AMPLIFIER XM-16A WITH THE MARK 8 SERVO MOTOR

A - With No Added Inertia.

43. The Mark 8 servo motor has a corner frequency, ω_1, of approximately 20 radians per second. This was found by making a frequency analysis of an uncompensated closed loop system involving the Mark 8 motor with no added friction or inertia. The control phase windings of the motor were in series. The fixed phase winding was operated in series with a 0.33 µf capacitor.

44. Following the servo design technique previously discussed, the lower break frequency of the lead network was set at 35.1 radians per second for the low gear ratios. The voltage taken from the divider composed of R_1 and R_2, figure 2, was reduced until there was no lead circuit instability due to excessive gain around the feedback loop. The attenuating resistance, R_a, was adjusted for the desired resonant rise of the system which was 2.28 db.

45. The compensated system was evaluated over a range of gear ratios. The values of the feedback network components for each gear ratio used are given in Table VI. Also shown is the lower break frequency, ω_2, as set for each gear ratio and the ratio, ω_2/ω_1. The network values given illustrate only one possible combination of values. Other combinations within the restrictions given by the equations of figure 2, will produce the same performance or some desired variation in performance such as increased bandwidth with less damping.

46. For the networks given in Table VI the performance of the compensated system with the Mark 8 motor and no added inertia is shown in figure 16. Curve a, figure 16, shows the bandwidth extension over the uncompensated bandwidth of 20 radians per second. Curve b, figure 16, shows the static error in degrees at the control transformer shaft. Curve c, figure 16 shows the velocity constant in degrees per second of angular velocity at the control transformer per degree error signal.

B - With Added Inertia

47. To present a more complete picture of the operation of Magnetic Control Amplifier XM-16A with the Mark 8 servo motor it was desired to give the performance under different load conditions. To this end inertia loads were added to the system.

48. The moment of inertia of the Mark 8 servo motor is 0.0191 in^2 oz. This moment of inertia is represented as J_{m8} and is the total moment of inertia in systems using the Mark 8 motor with no added inertia, assuming the gear train inertia can be neglected. To this system was added a moment of inertia equal to 3.03 times the motor inertia, J_{m8}. This made a total moment of inertia equal to 4.03 J_{m8}. Under this load condition the uncompensated system bandwidth, ω_1 of figure 1, was lowered to 5.0 radians per second.

49. The lower break frequency of the lead network was set at 22.8 radians per second for the low gear ratios and lowered somewhat at higher gear ratios. The network values for this load condition are given in Table VII and the performance of the system at various gear ratios given in figure 17.

50. To present another load condition representing a more difficult damping problem, a larger inertia was added to the system. A moment of inertia of 5.18 times the Mark 8 motor inertia was added to the system making a total moment of inertia equal to 6.18 J_{m8}. Under this load condition the uncompensated system bandwidth was lowered to 3.2 radians per second. Upon applying compensation the performance curves of figure 18 were obtained using the network component values given in Table VIII. Here, for the 19.25:1 gear ratio the bandwidth was extended from 3.2 radians per second out to 83 radians per second, a factor of 26.

51. Data for an additional value of inertia load for the Mark 8 motor is obtainable in this report. The Mark 16, servo motor corresponds to a Mark 8 motor with tachometer generator added. The tach generator adds an inertia of 0.64 times the motor inertia which in a system with no other inertia presents a total inertia of 1.64 J_{m8}. As seen in the Performance Section for the Mark 16, motor, this motor was operated with network compensation. That is, the tachometer generator was not used for damping but merely added its inertia to the system. The performance of the system under this load condition is shown in figure 20 for feedback network component values given in Table X. The addition of a frictional load to the system would extend the bandwidth and present the designer with a less acute damping problem. Since such a system demands increased amplifier gain and motor output torque rather than bandwidth extension it was felt that discussion of this type of load was beyond the scope of this paper.

52. The Magnetic Control Amplifier XM-16A is therefore shown to be applicable for operation with the Mark 8 servo motor under a variety of load conditions and over a range of gear

ratios from 19.25 to 1155. At gear ratios higher than this the basic amplifier can still be used without compensation (See figure 8b) although the gain limitation of the amplifier is approached.

C - A Special Case of Operation

53. It is not necessary that the negative integral feedback discussed in the Servo Design section be placed around three stages of the magnetic amplifier. A similar lead characteristic can be obtained with negative integral feedback around two stages of the magnetic amplifier but with less gain available for break frequency spread. In the preliminary stage of investigation, performance curves were taken of the Magnetic Control Amplifier XM-16A with feedback around the first two stages. It was operated with the Mark 8 motor having parallel control phase windings and no added load inertia.

54. With reference to figure 2, feedback around only two stages means that K now represents the dc gain of the first two stages while the third stage is placed following the attenuating resistance R_a. The phase of the input to the integration network has suffered a 180° shift in the elimination of a stage of amplification which necessitates a reversal of the sense of the feedback.

55. The system was evaluated over a range of gear ratios from 3.85 to 770 using feedback around two stages. Above this ratio the amplifier was operated without compensation and evaluated up to a gear ratio of 3850. In all cases the system was damped to a resonant rise of 2.28 db which is a phase margin of 45 degrees. The values of network components all remained fixed with only the value of R_a varying with gear ratio. These values are given in Table IX and the performance of the system with feedback shown in figure 19.

56. It is apparent that there may be some special advantages to compensation involving feedback around two stages. Although the bandwidth extension will be generally lower it is possible to work at very low gear ratios. The static error increases at these low ratios, however. In presenting the data for this special case of operation it was desired to show another aspect of the flexibility of the basic amplifier. The amplifier can be adapted for feedback around two stages as well as three stages by the addition of three pin connections in the Winchester plug provided for the external components.

PERFORMANCE OF THE MAGNETIC CONTROL AMPLIFIER XM-16A WITH THE MARK 16 SERVO MOTOR

A - With No Added Inertia And Lead Compensation.

57. The Mark 16 servo motor has a corner frequency ω_1, of approximately 15 radians per second. This was found by making a frequency analysis of an uncompensated closed loop system around the Mark 16 motor with no added friction or inertia. The control phase windings of the motor were connected in series. The fixed phase winding was operated in series with a 0.33 µf capacitor. The tachometer generator was not used for damping and the system was damped to a resonant rise of 2.28 db by attenuating amplifier gain.

58. In order to provide compensation for this system having a bandwidth of approximately 15 radians per second, the lower break frequency, ω_1, of the lead network was set at 31.7 radians per second at the lower gear ratios and reduced at higher gear ratios. The voltage taken from the divider, composed of R_1 and R_2, figure 2, was reduced until there was no lead circuit instability due to excessive gain around the feedback loop. The attenuating resistance, R_a, was adjusted for the desired resonant rise of 2.28 db.

59. The compensated system was evaluated over a range of gear ratios from 20 to 1200. The values of the feedback network components for each gear ratio at which the system was evaluated are given in Table X. Also shown is the lower break frequency as set for each gear ratio and the ratio ω_2/ω_1. Again it should be noted that the network values given were chosen to illustrate the procedure and performance and represent only one possible combination of these values.

60. The performance of the system is shown in figure 20. The stabilization of this system without the use of the tachometer generator for damping leaves the tachometer generator free for other uses in the system. Here then is provided a system with a signal voltage available that is proportional to velocity. This may be of interest in some applications. In many cases however the tachometer generator will be used for damping the system in which case the Magnetic Control Amplifier XM-16A is used without external feedback networks as shown in figure 8b.

B - With No Added Inertia and Tachometer Damping.

61. As stated before, the Mark 16 servo motor has a corner frequency of approximately 15 radians per second. Using tach damping in this system with no added inertia, the corner

frequency was extended to 105 radians per second at a gear ratio of 20:1. There exists a limitation on the extension of this bandwidth due to amplifier and tachometer phase shift[6] The performance over the range of gear ratios is shown in figure 21. With the feedback network not being used, the variable external components remaining are R_c and R_a with the addition of a new component, R_t, in series with the tachometer generator. The external connections are shown in figure 8b while the internal connections are seen in figure 6. It can be seen that feeding the speed proportional signal from the tachometer into pins 7 and 8 of the Magnetic Control Amplifier XM-16A with R_t in place as shown by figure 8b, results in the tach feedback being applied directly to the input control windings of the magnetic amplifier through R_t. Thus the tach feedback is in parallel with the control transformer input.

62. The values of the external components used in obtaining the performance curves of figure 21 are shown in Table XI.

C - With Added Inertia and Tachometer Damping.

63. In order to obtain a complete picture of the operation of the Magnetic Control Amplifier XM-16A with the Mark 16 motor employing tach damping rather than lead compensation it was desired to check several load conditions. To this end two different inertia loads were added to the system.

64. The first added inertia equalled 0.41 times the Mark 16 motor inertia, J_{m16}, giving a total inertia equal to 1.41 J_{m16}. The Mark 16 motor moment of inertia, J_{m16}, including motor and tachometer generator, equals 0.0313 in^2 oz. With this load condition the uncompensated system bandwidth is approximately 10.6 radians per second. Employing tachometer damping the performance curves of figure 22 were obtained with the external component values given in Table XII.

65. The second inertia load investigated was with the addition of an inertia equal to 2.48 times the motor inertia which gave a total inertia equal to 3.48 J_{m16}. With this load condition the uncompensated system bandwidth was approximately 4.3 radians per second. Employing tach damping the performance curves of figure 23 were obtained with external component values given in Table XIII.

66. The Magnetic Control Amplifier XM-16A is seen to be applicable for operation with the Mark 16 servo motor under a variety of load conditions and over a range of gear ratios of 20 to 1200. Damping may be accomplished by tachometer

feedback or by lead network compensation. The effect of additional inertia loading on systems using the Mark 16 motor and employing lead network compensation can be determined by consulting the curves for the Mark 8 motor with added inertia loading. The Mark 16 motor moment of inertia, J_{m16}, is 1.64 times the Mark 8 motor moment of inertia, J_{m8}.

PERFORMANCE OF THE MAGNETIC CONTROL AMPLIFIER XM-17A WITH THE MARK 14 SERVO MOTOR

A - With No Added Inertia.

67. The Mark 14 servo motor has a corner frequency, ω_1, of approximately 9 radians per second. This was determined by frequency response analysis of an uncompensated closed loop system using the Mark 14 motor with the control phase windings in parallel. The fixed phase winding was connected in series with a 0.1 µf capacitor.

68. For this 9 radians per second bandwidth the lead network lower break frequency, ω_2, was set at 20 radians per second for the low gear ratios and reduced to 16 radians per second for ratios greater than 520:1. The attenuating resistance, R_a, was adjusted for the desired resonant rise of the system of 2.28 db.

69. The compensated system was evaluated over a range of gear ratios. The values of the feedback network components for each gear ratio checked are given in Table XIV. The performance of the system is shown in figure 24. The 9 radians per second bandwidth is seen to be extended to 134 radians per second at a gear ratio of 28.9:1, a factor of 14.9.

B - With Added Inertia.

70. The rotor moment of inertia, J_{m14}, of the Mark 14 servo motor is 0.00585 in^2 oz. To check performance of the system with added inertia load, sufficient inertia was added to bring the total inertia including that of the motor up to 3 J_{m14}. With this load condition the uncompensated system bandwidth is lowered to 3 radians per second.

71. The lower break frequency, ω_2, of the lead network is set between 16 and 21.5 radians per second over the gear ratio range. Specific values are shown in Table XV along with the values of feedback network components used at various gear ratios. The voltage taken from the divider composed of R_1 and R_2, figure 2, was reduced until there was no lead circuit

instability due to excessive gain around the feedback loop. The attenuating resistance, R_a, was adjusted for the desired resonant rise of 2.28 db.

72. The performance of the system is shown in figure 25. The 3 radians per second bandwidth was extended to 69 radians per second at a gear ratio of 28.9:1. This is a factor of 23.

73. The addition of a frictional load to the system would extend the bandwidth and present the designer with a less acute damping problem. Since such a system demands increased amplifier gain and motor output torque rather than bandwidth extension it was felt that discussion of this type load was beyond the scope of this paper.

74. The Magnetic Control Amplifier XM-17A is therefore shown to be applicable for operation with the Mark 14 servo motor under several load conditions and over a range of gear ratios from 28.9 to 1733. At gear ratios higher than this the basic amplifier can still be used without compensation as in figure 8b, although the gain limitation of the amplifier is approached.

CONCLUSION

75. The design of a servo system employing a magnetic control amplifier with lead compensation is simple, straightforward and accurate. Using this design technique with a given motor, a basic control amplifier can be constructed which can be modified externally by a plug-in unit to meet a wide variety of system requirements.

76. Such a basic control amplifier has been constructed for operation with servo motors, Mark 7, Mark 8, and Mark 16, and another for operation with servo motor Mark 14.

77. The complete construction details and performance curves for both magnetic control amplifiers anticipate the requirements of many systems and can be used to predict the performance of these amplifier-motor combinations in a specified system.

78. System requirements not covered by the performance curves but necessitating lead compensation within the scope of this report may be met with these amplifier-motor combinations by the design of a simple RC network.

79. The possibilities of the basic amplifier have not been exhausted. Other types of compensation may be used to meet specific system requirements.

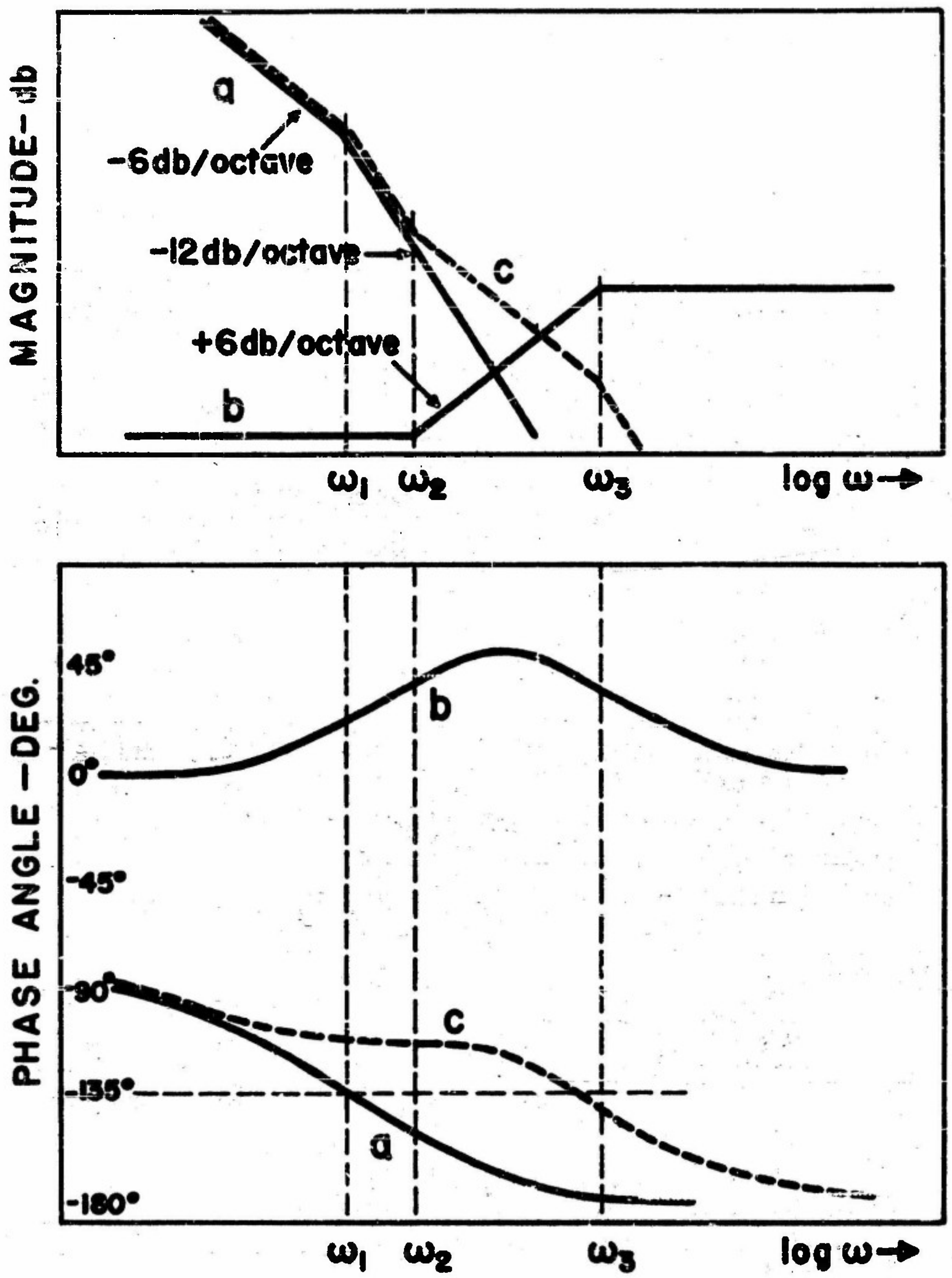
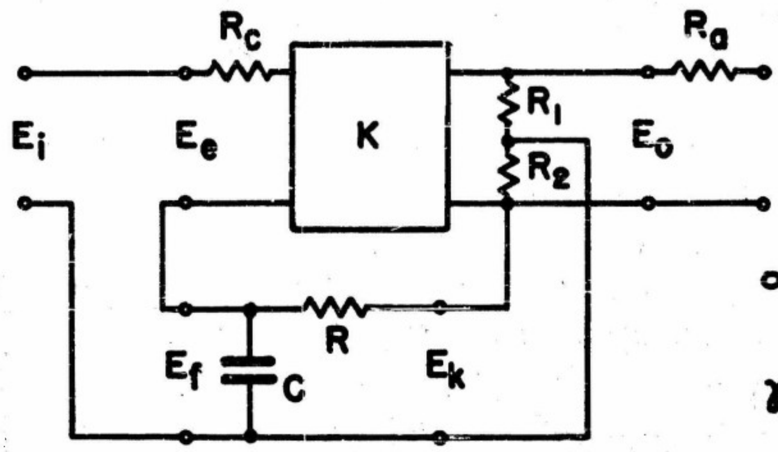


FIG. 1 — LEAD COMPENSATION



$$T = RC$$

$$\alpha = \frac{R_c}{R_c + R}$$

$$\gamma = \frac{R_1 R_2}{R_1 + R_2}$$

$$K = \frac{\text{dc component of } E_o}{E_e} = \text{dc gain}$$

for $R_1 = 0$

$$\frac{E_o}{E_i} = \frac{\frac{K}{1+\alpha K}(\alpha T j\omega + 1)}{\frac{1}{1+\alpha K}\alpha T j\omega + 1} \qquad \frac{E_f}{E_k} = \frac{\alpha}{\alpha T j\omega + 1}$$

lower break frequency = $1/(\alpha T)$
break frequency spread = $1 + \alpha K$
zero frequency gain = $K/(1+\alpha K)$

for $R_1 > 0$

$$\frac{E_o}{E_i} = \frac{\frac{K}{1+\alpha'\beta K}(\alpha' T j\omega + 1)}{\frac{1}{1+\alpha'\beta K}\alpha' T j\omega + 1} \qquad \frac{E_f}{E_k} = \frac{\alpha'\beta}{\alpha' T j\omega + 1}$$

lower break frequency = $1/(\alpha' T)$
break frequency spread = $1 + \alpha'\beta K$
zero frequency gain = $K/(1+\alpha'\beta K)$
where:

$$\alpha' = \alpha \left[\frac{1 + \frac{\gamma}{R}}{1 + \frac{\gamma}{R + R_c}} \right] \qquad \beta = \frac{R}{R + \gamma}$$

FIG. 2 — CIRCUIT FOR LEAD COMPENSATION

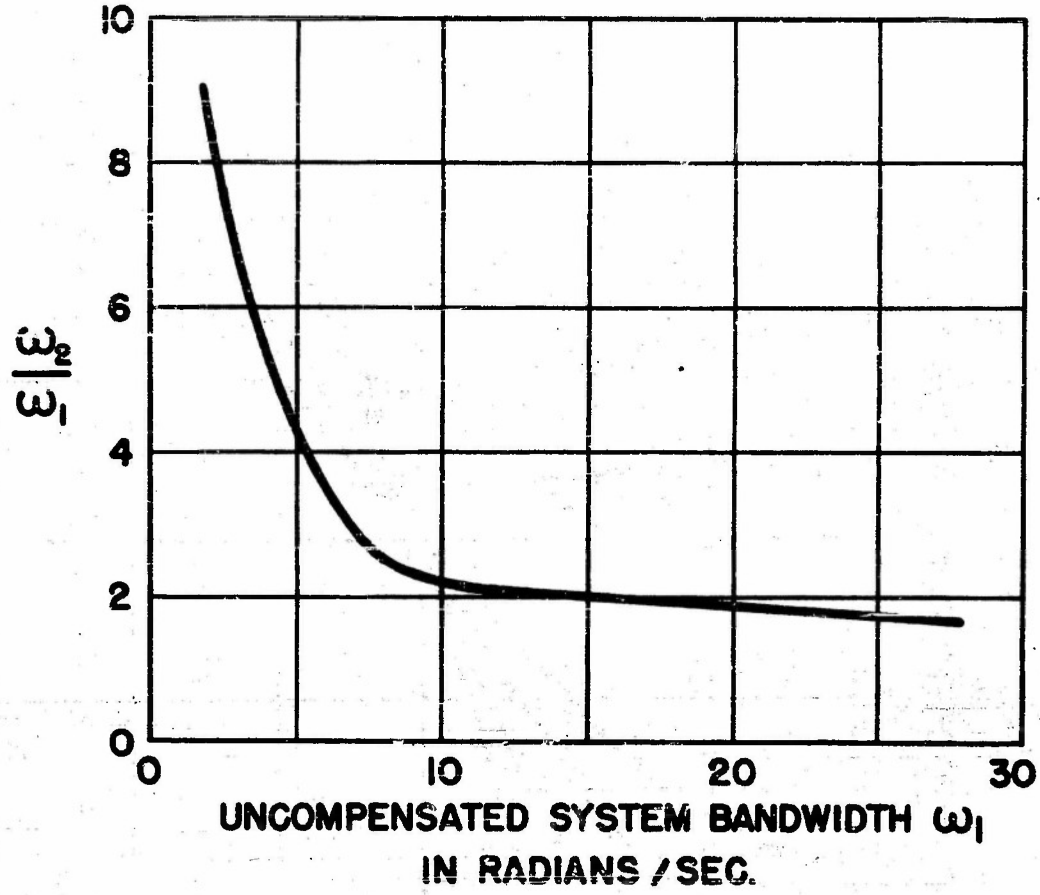


FIG. 3 — DESIGN CURVE FOR SETTING LOWER BREAK FREQUENCY

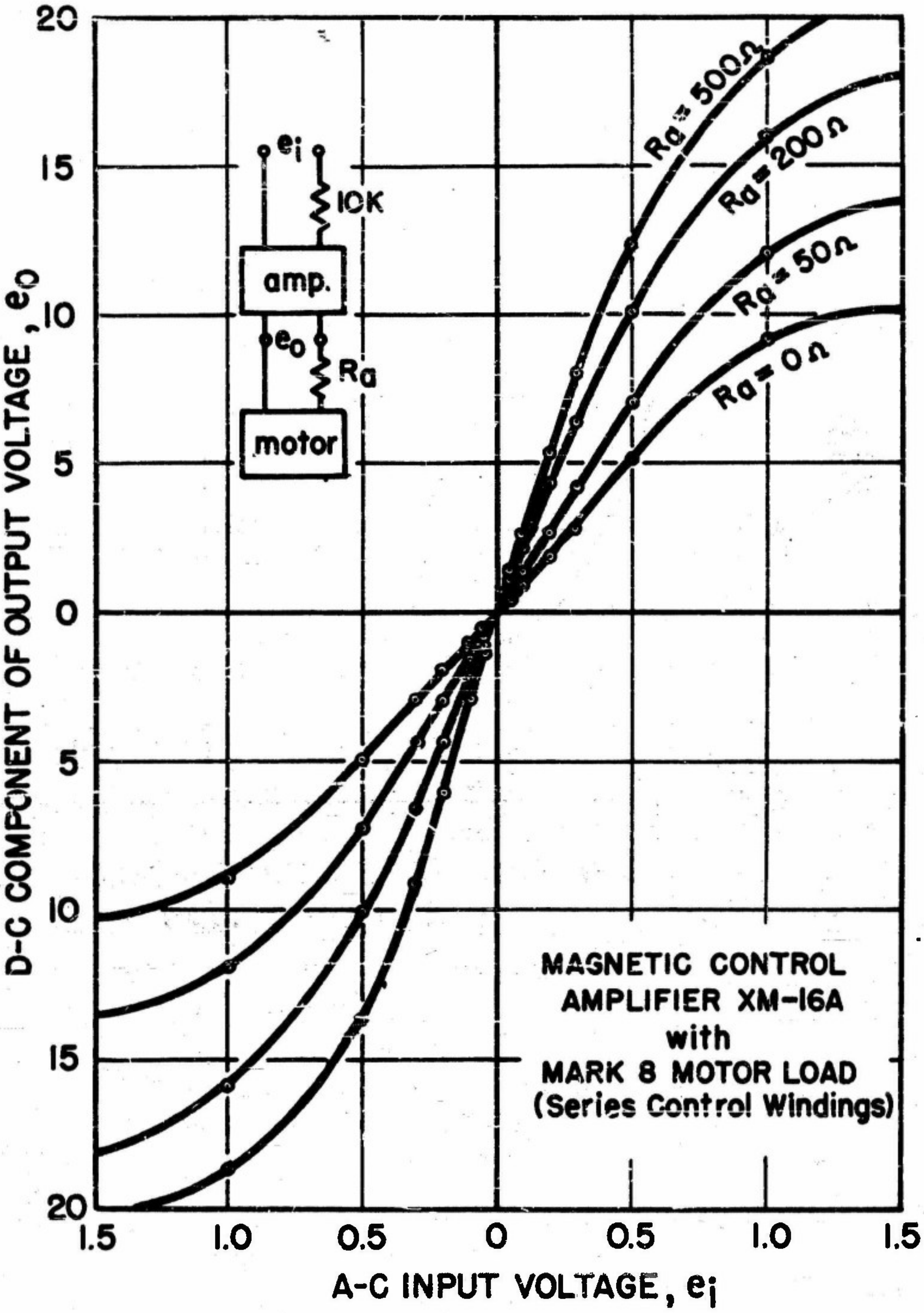


FIG. 4 — D-C COMPONENT OF OUTPUT VOLTAGE OF MAGNETIC CONTROL AMPLIFIER XM-16A

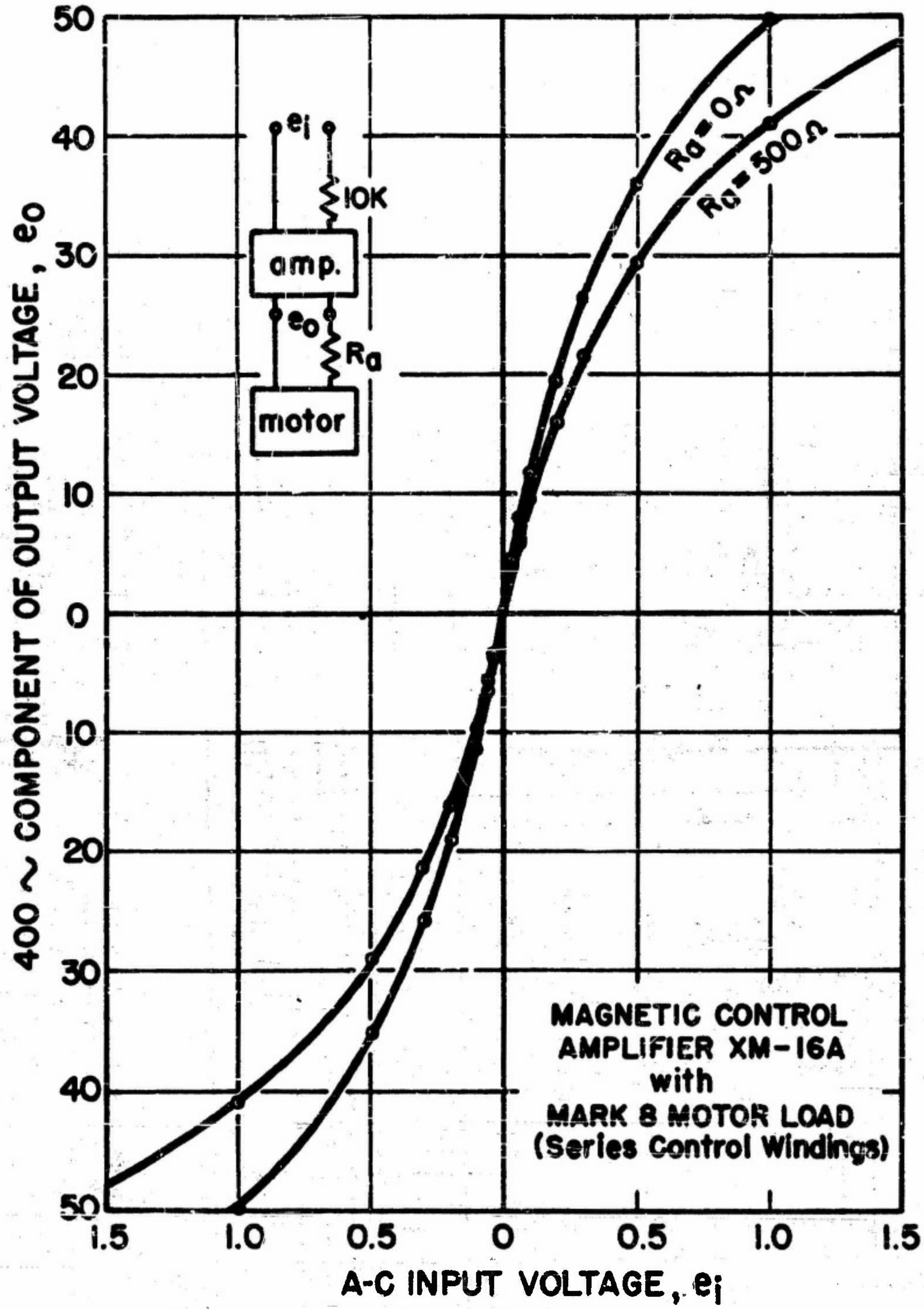


FIG. 5 — 400 ~ COMPONENT OF OUTPUT VOLTAGE OF MAGNETIC CONTROL AMPLIFIER XM-16A

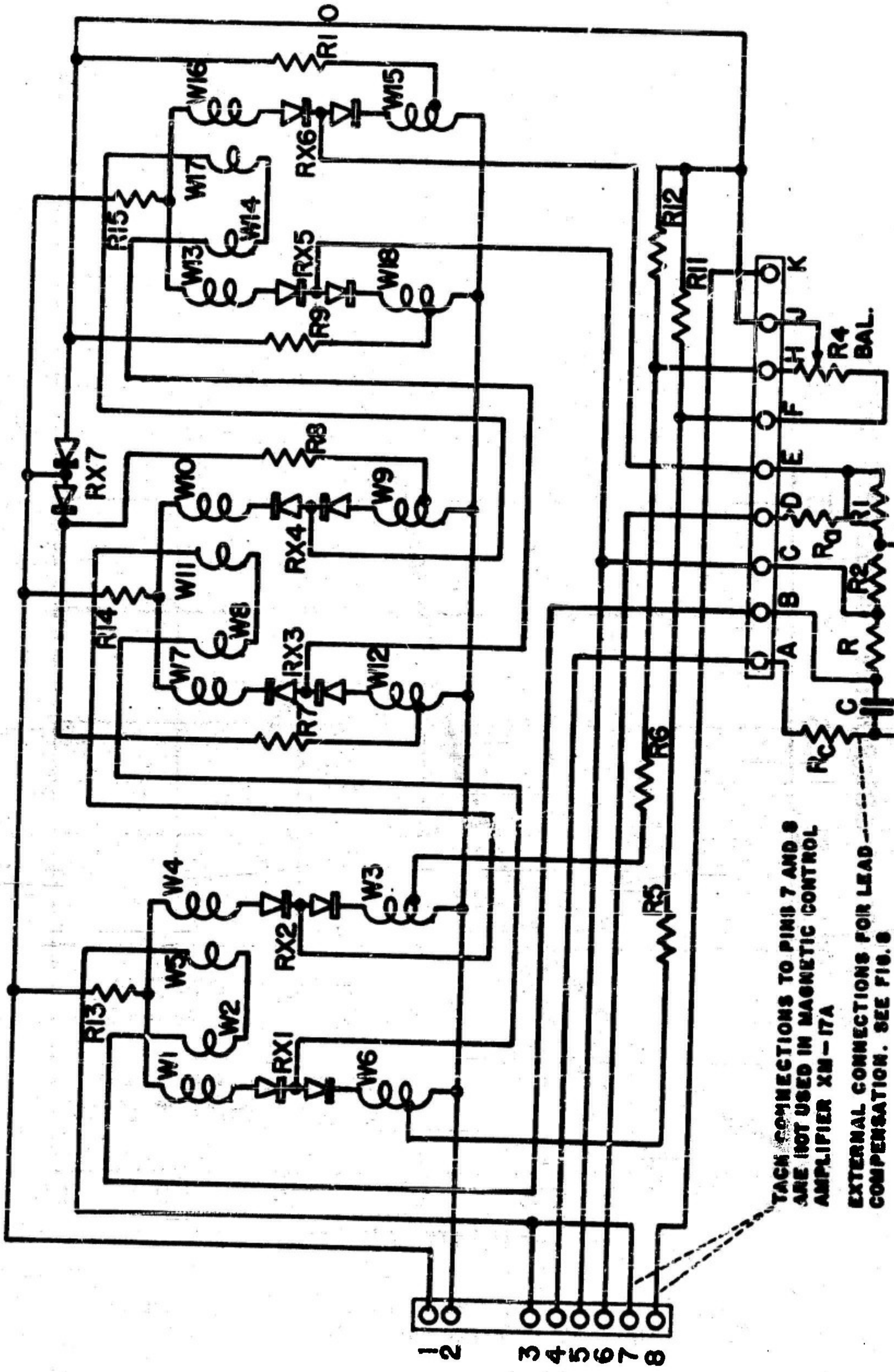


FIG. 6 — COMPLETE CIRCUIT DIAGRAM

All cores are toroidally wound 0.002" ORTHONOL (highly grain oriented 50% nickel-iron) tape having a rectangular hysteresis loop. These cores are placed in bakerlite cores boxes before winding. The boxes for the 5/8" X 1" X 1/4" cores have the inside wall removed to increase the winding space.

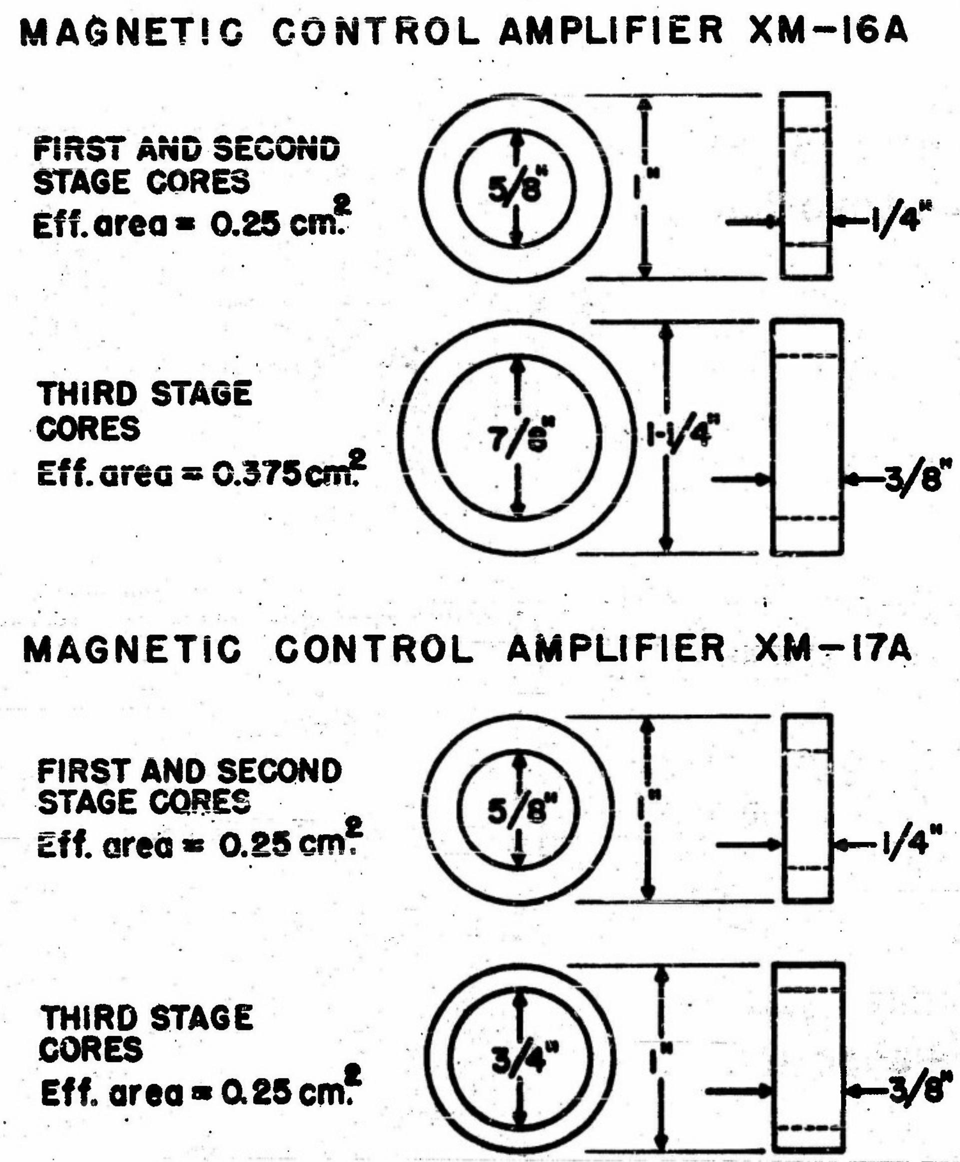


FIG.7 - CORE DIMENSIONS

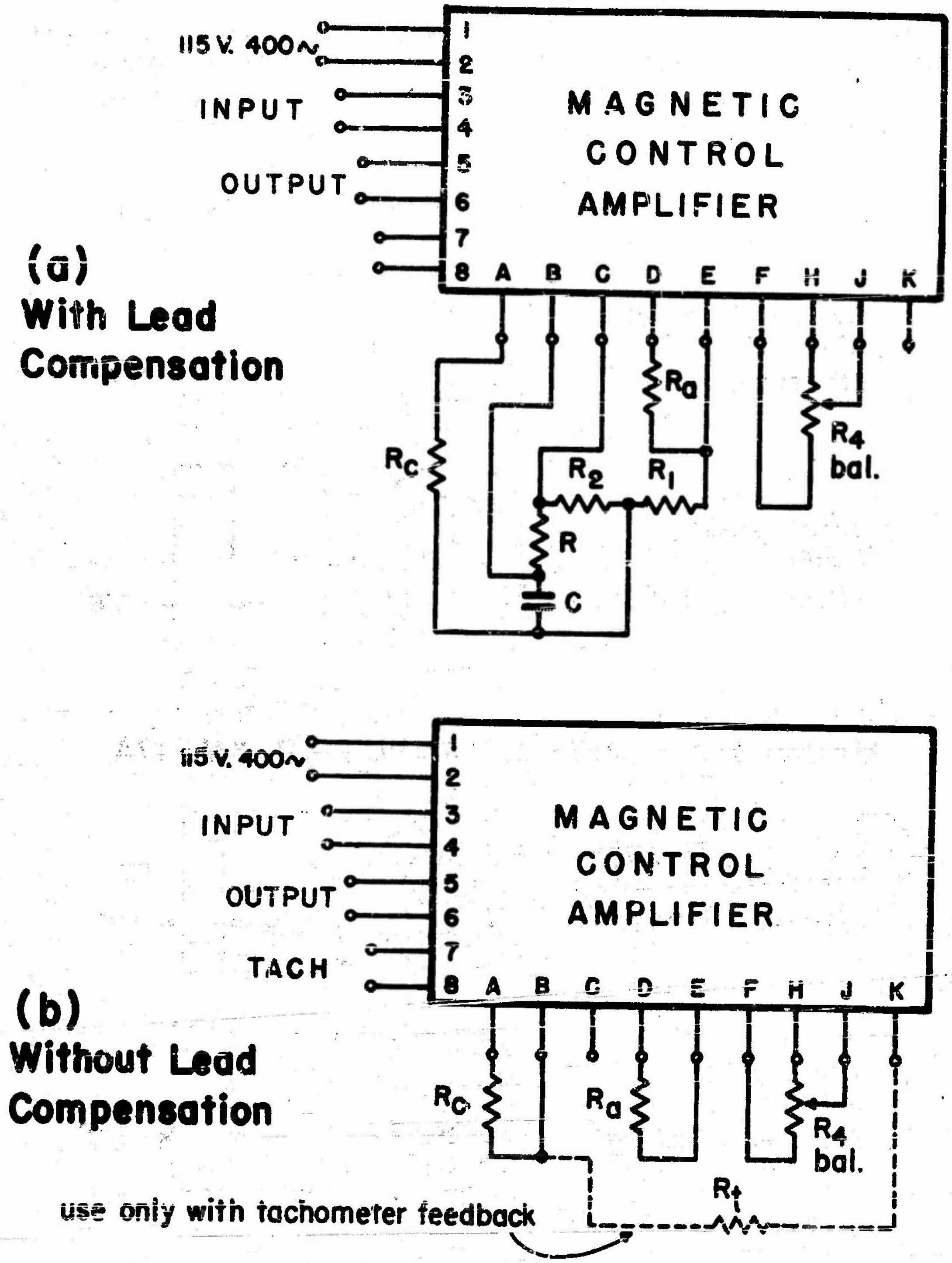


FIG. 8 - TERMINAL CONNECTIONS

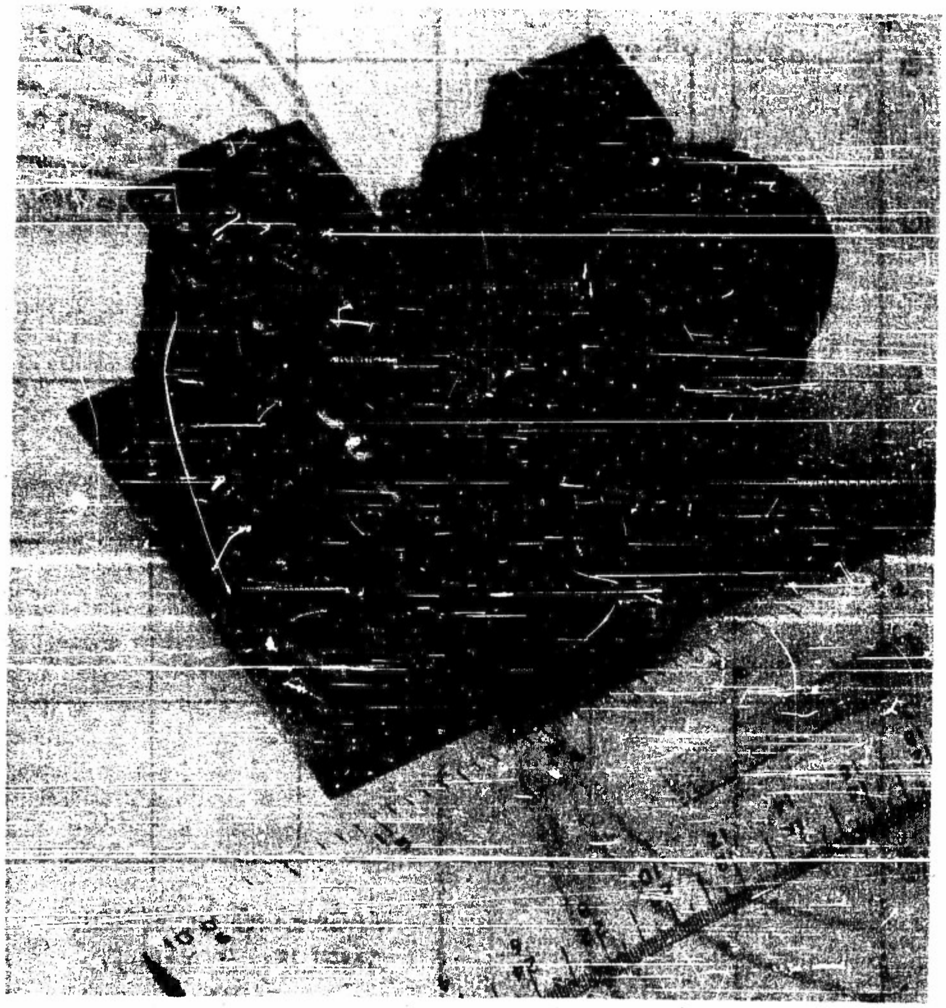


FIG. 9 – MAGNETIC CONTROL AMPLIFIER XM-16A

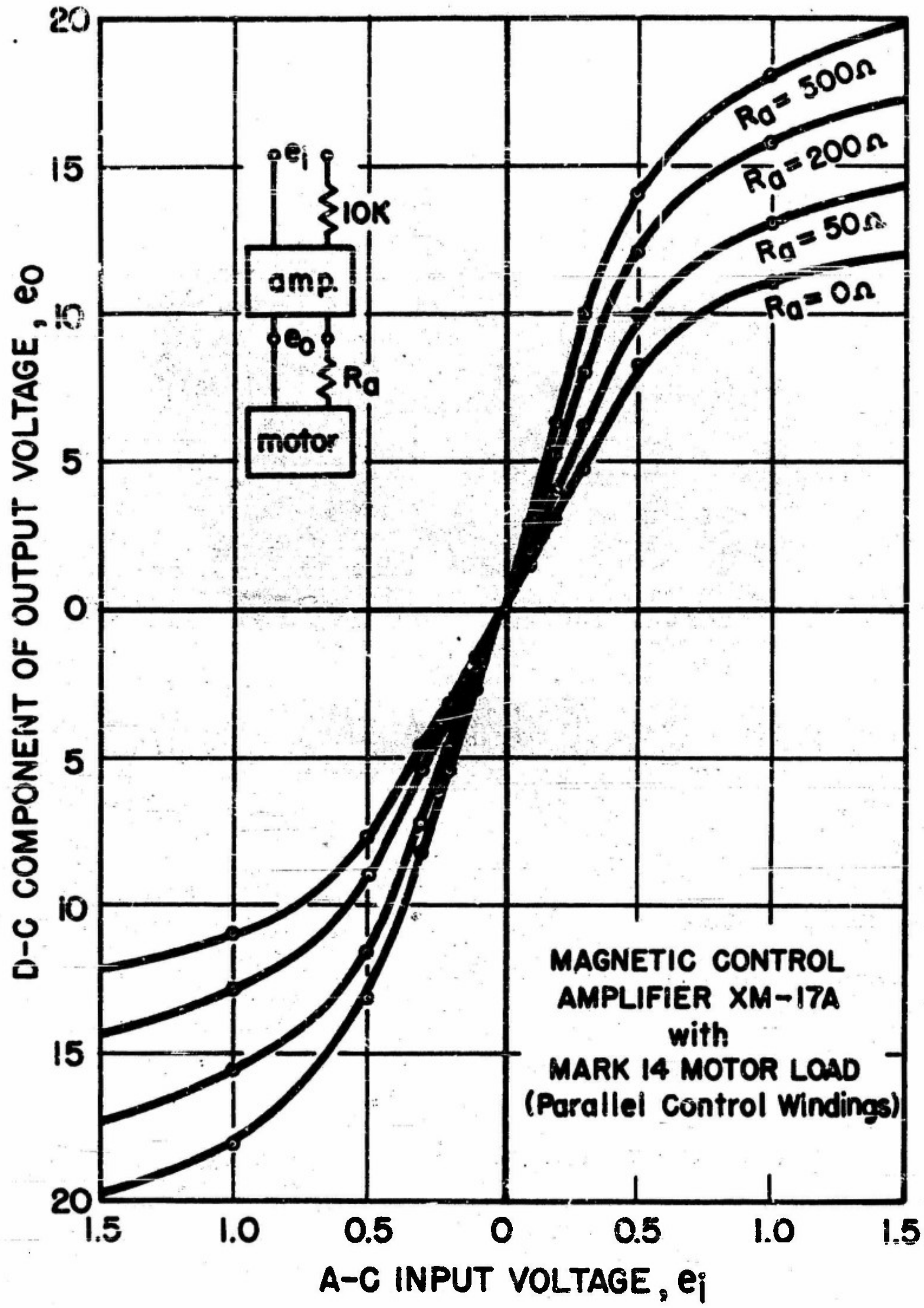


FIG. 10 – D-C COMPONENT OF OUTPUT VOLTAGE OF MAGNETIC CONTROL AMPLIFIER XM-17A

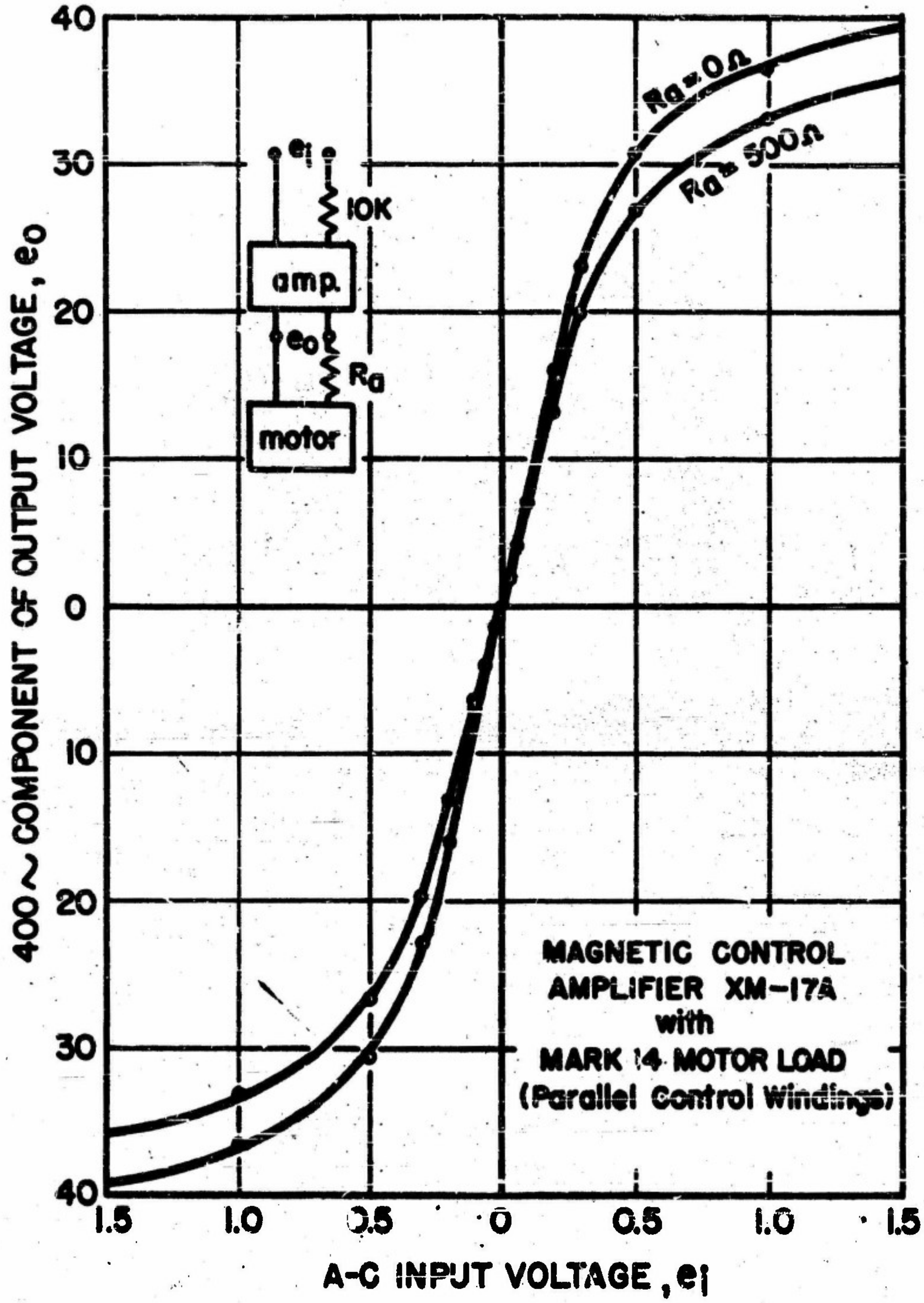


FIG. 11 – 400 ~ COMPONENT OF OUTPUT VOLTAGE OF MAGNETIC CONTROL AMPLIFIER XM-17A

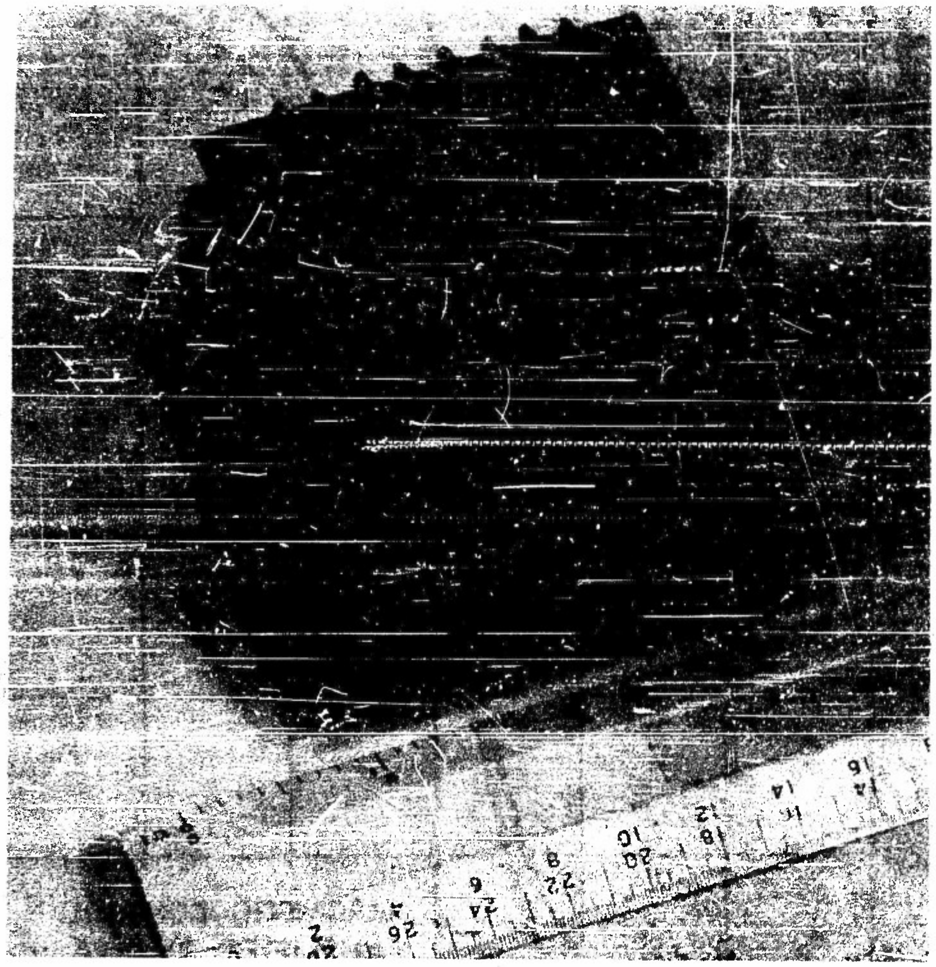


FIG. 12 — MAGNETIC CONTROL AMPLIFIER XM-17A

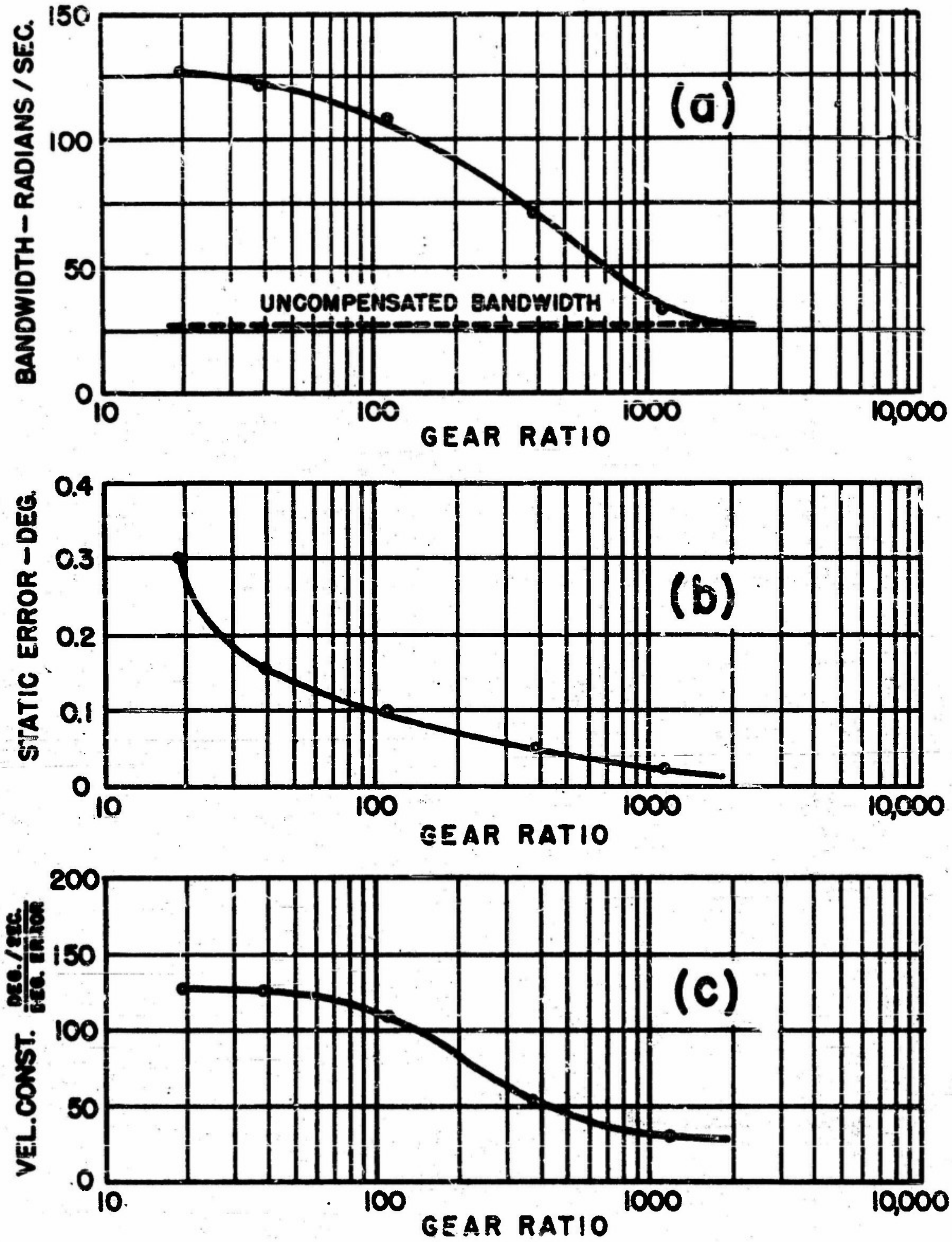


FIG. 13 — SYSTEM PERFORMANCE WITH MARK 7 MOTOR AND NO ADDED INERTIA

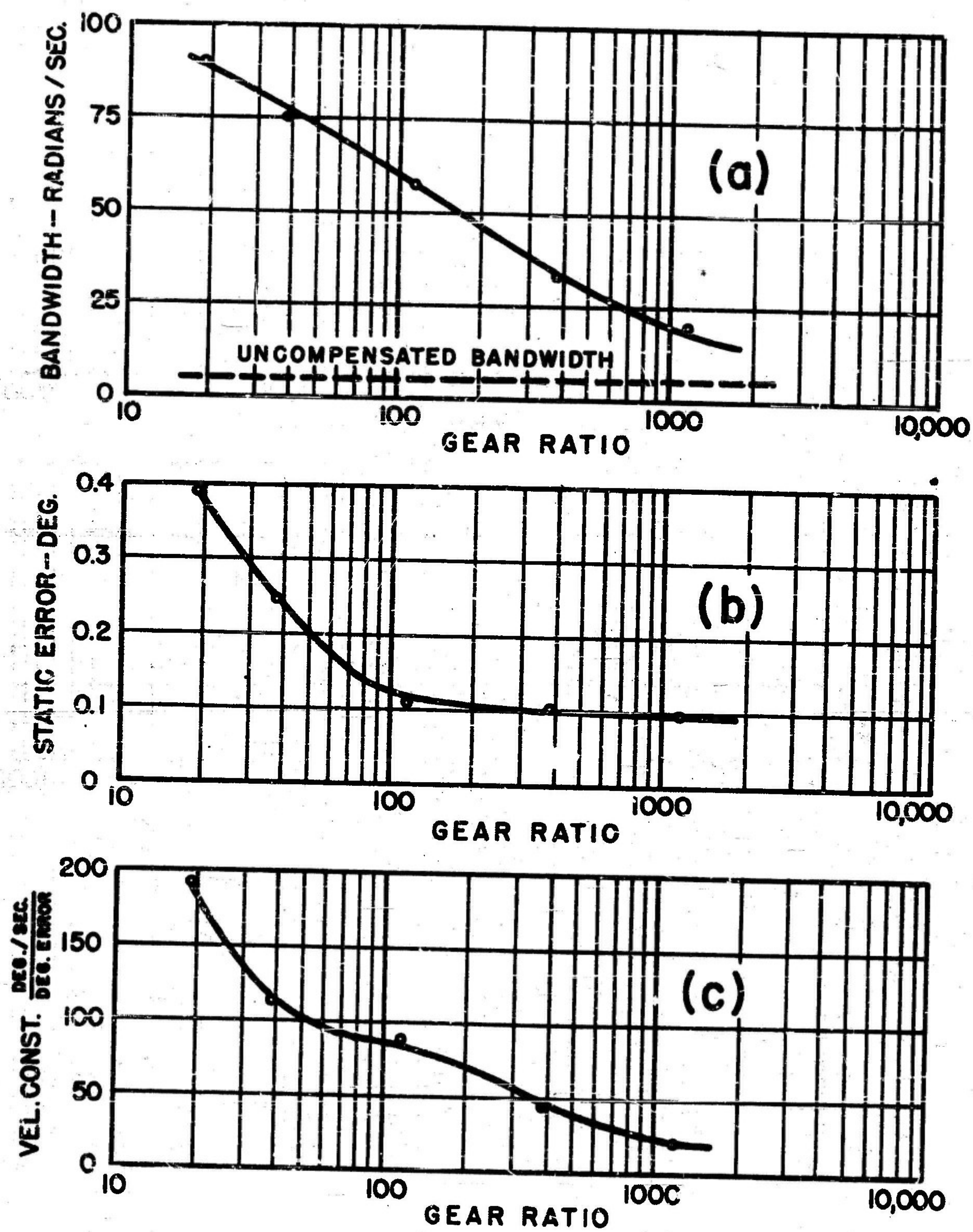
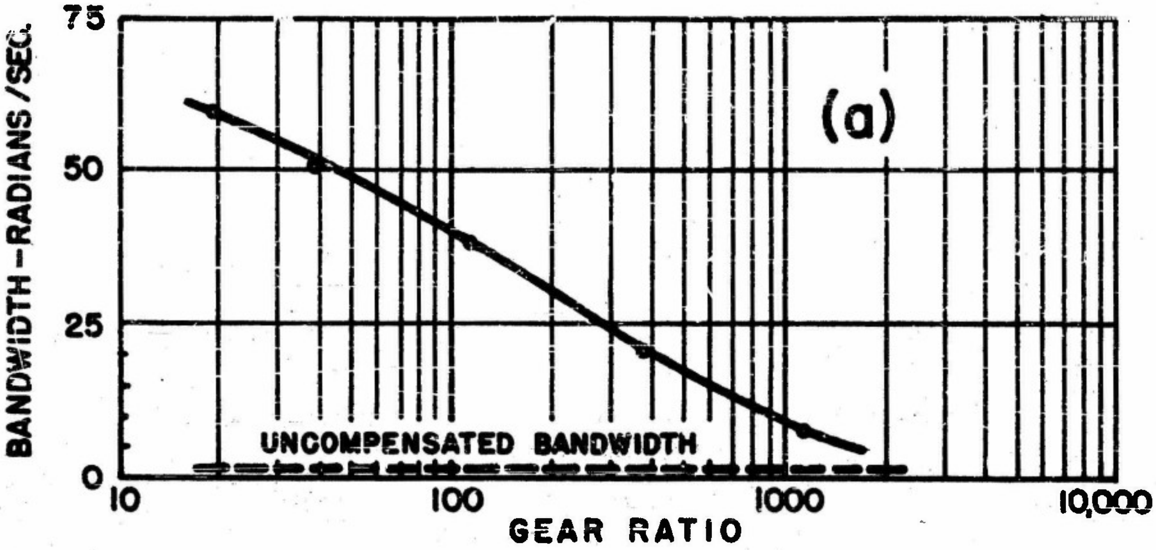
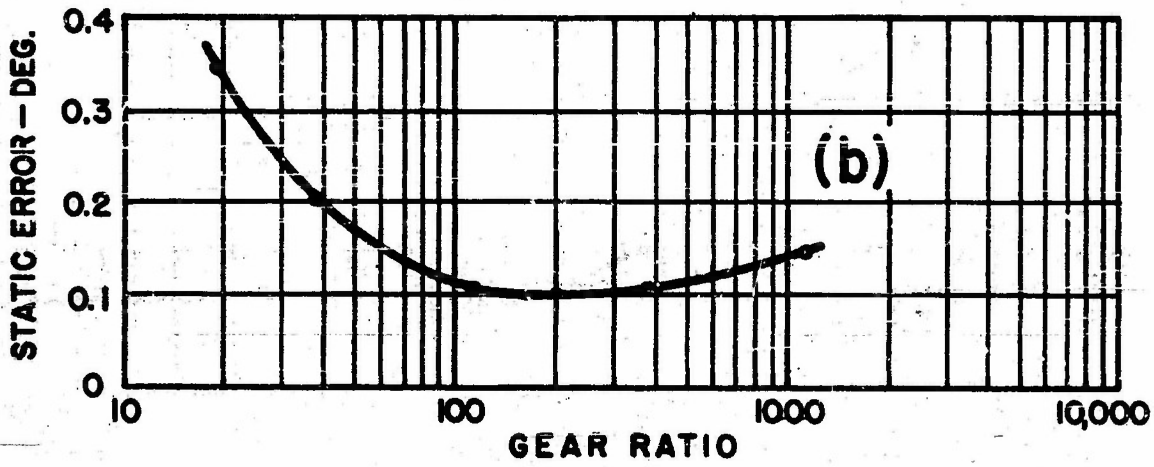


FIG. 14 — SYSTEM PERFORMANCE WITH MARK 7 MOTOR AND TOTAL INERTIA EQUAL 5.23 TIMES MOTOR INERTIA





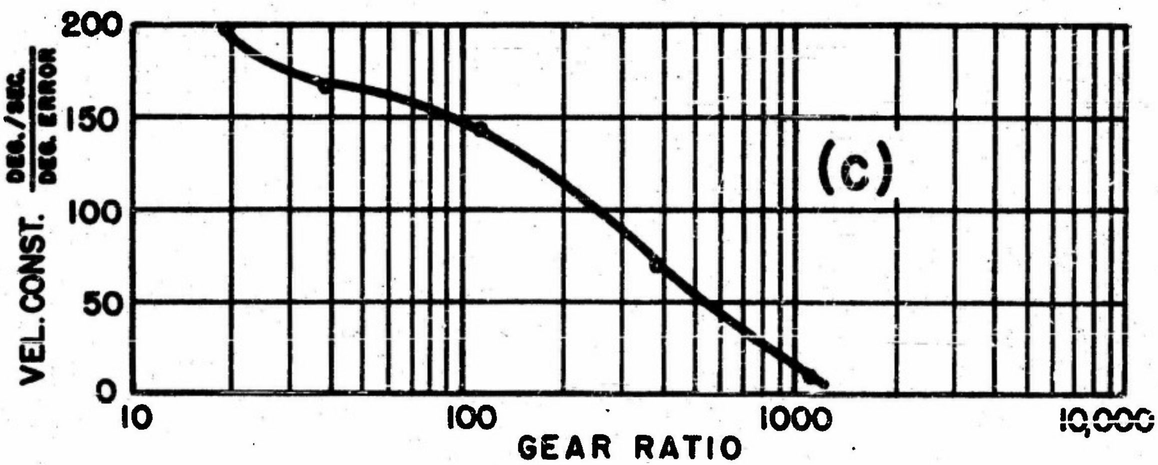


FIG. 15 — SYSTEM PERFORMANCE WITH MARK 7 MOTOR AND TOTAL INERTIA EQUAL 14.3 TIMES MOTOR INERTIA

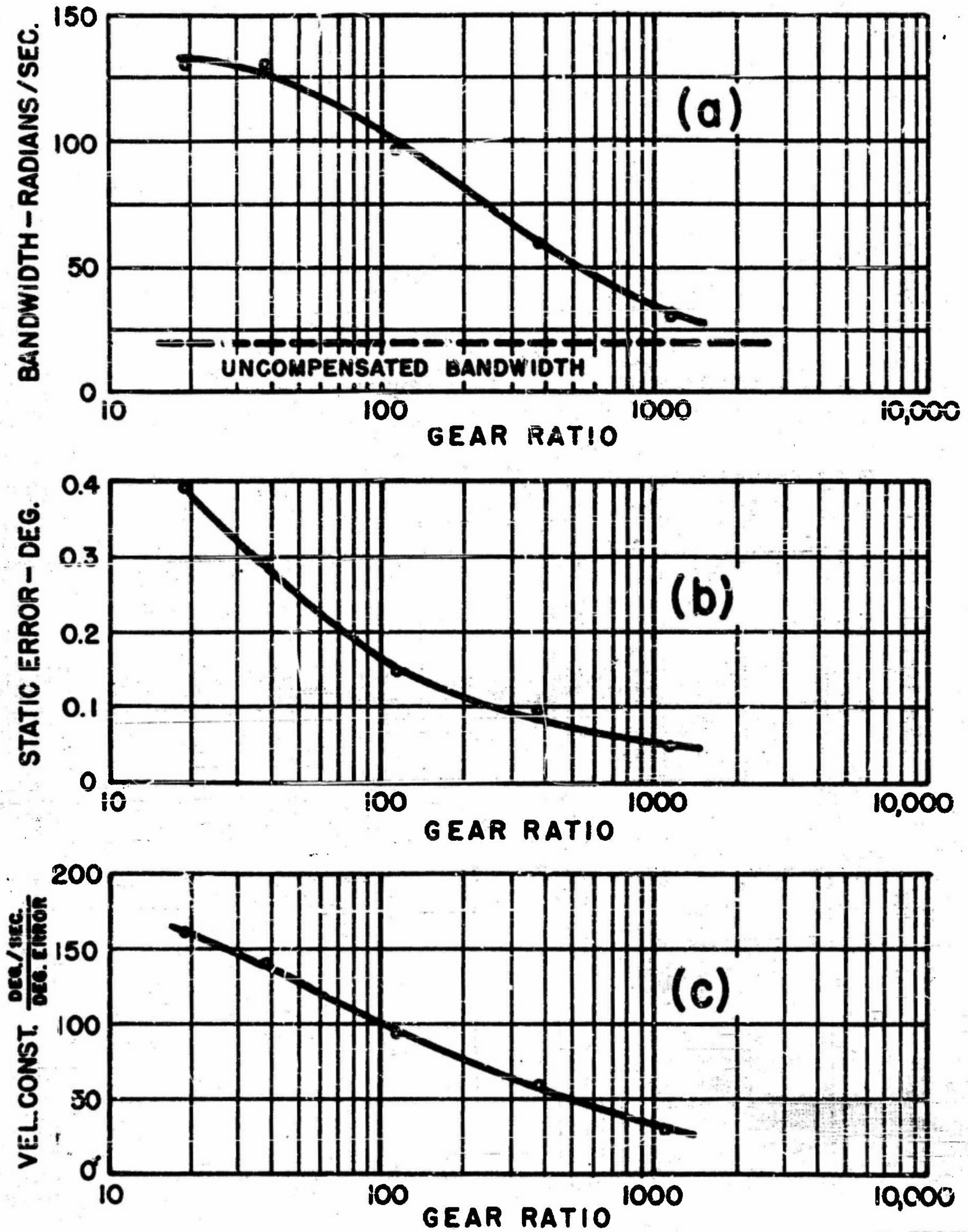


FIG. 16 — SYSTEM PERFORMANCE WITH MARK 8 MOTOR AND NO ADDED INERTIA

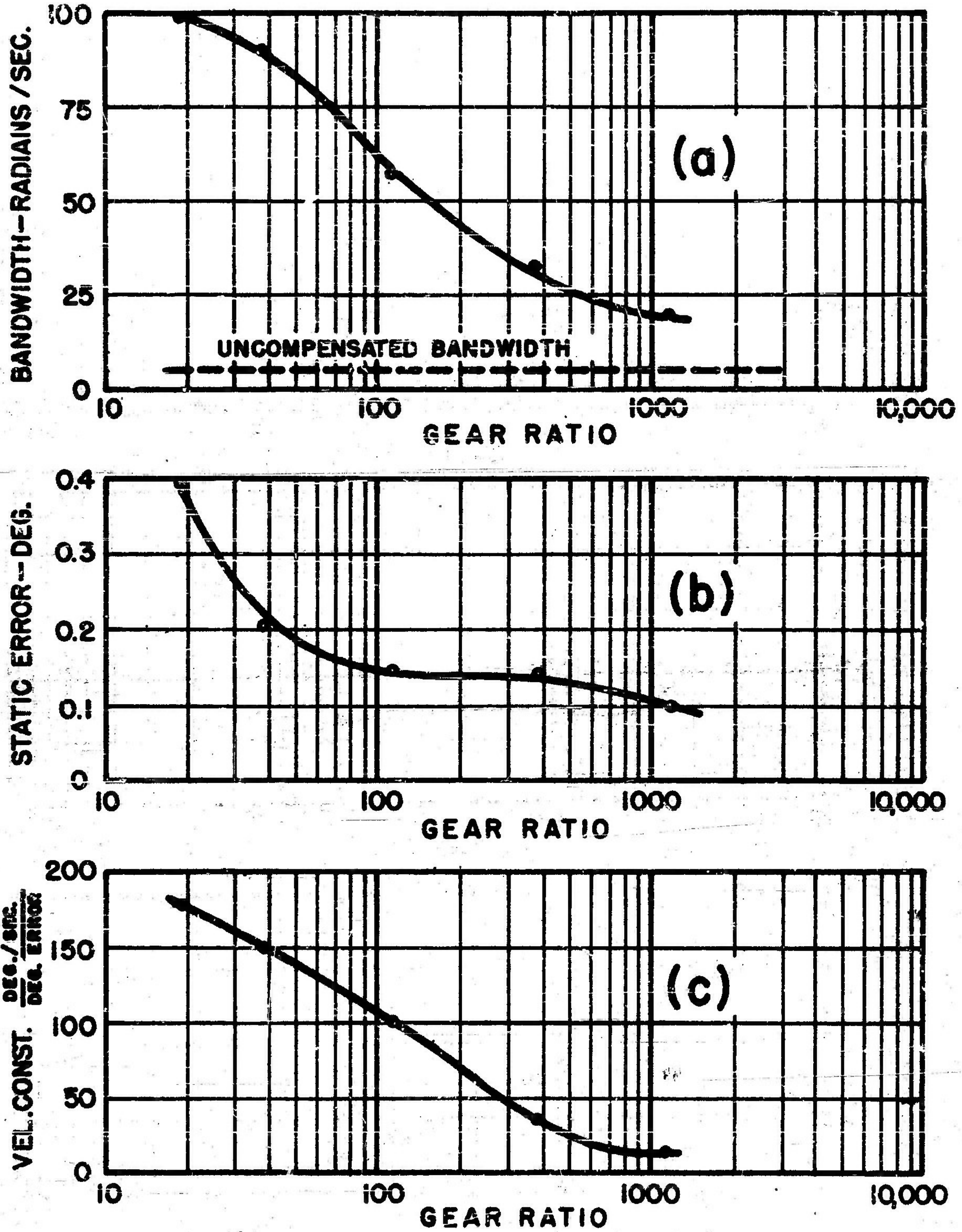


FIG. 17 — SYSTEM PERFORMANCE WITH MARK 8 MOTOR AND TOTAL INERTIA EQUAL 4.03 TIMES MOTOR INERTIA

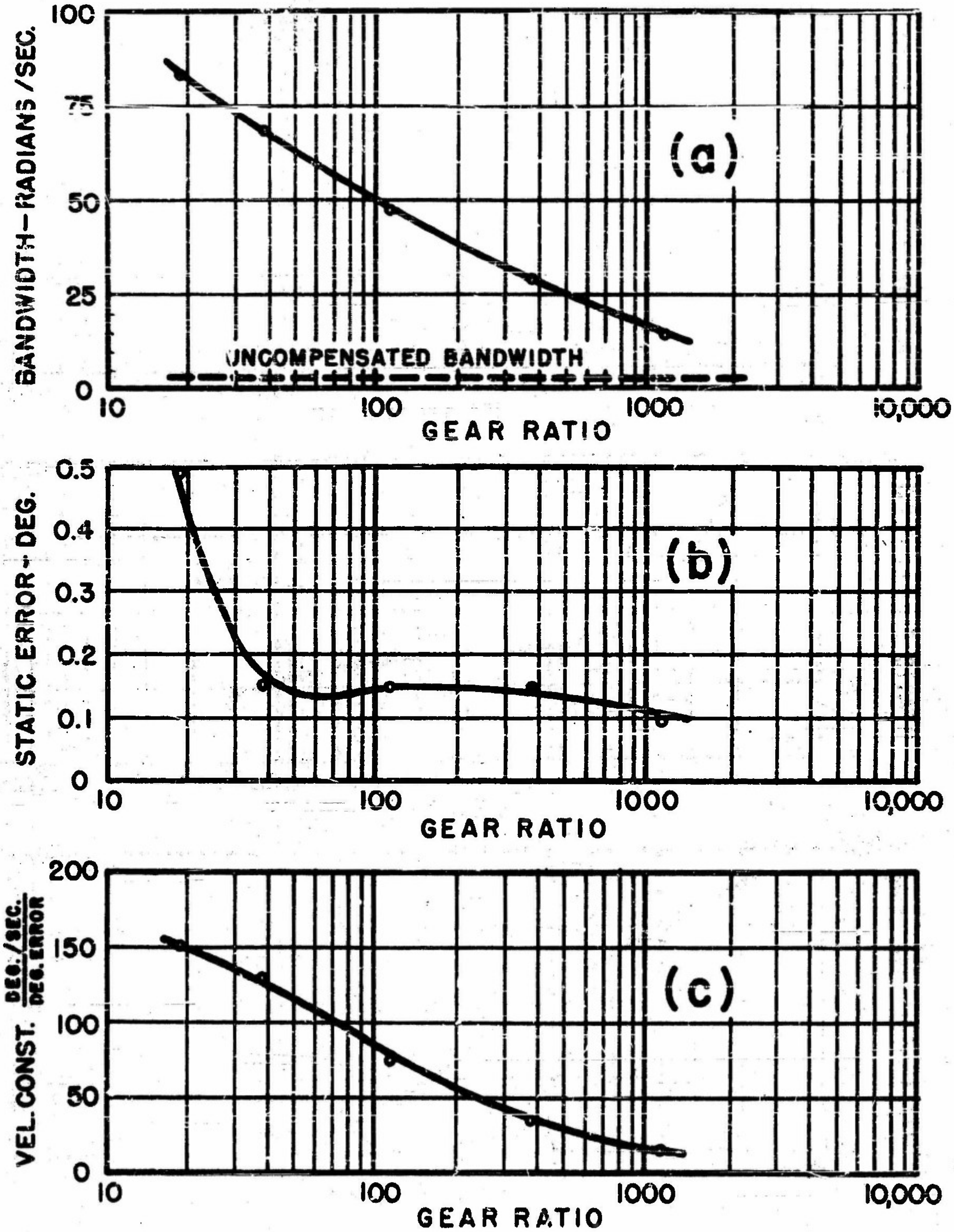


FIG. 18 — SYSTEM PERFORMANCE WITH MARK 8 MOTOR AND TOTAL INERTIA EQUAL 6.18 TIMES MOTOR INERTIA

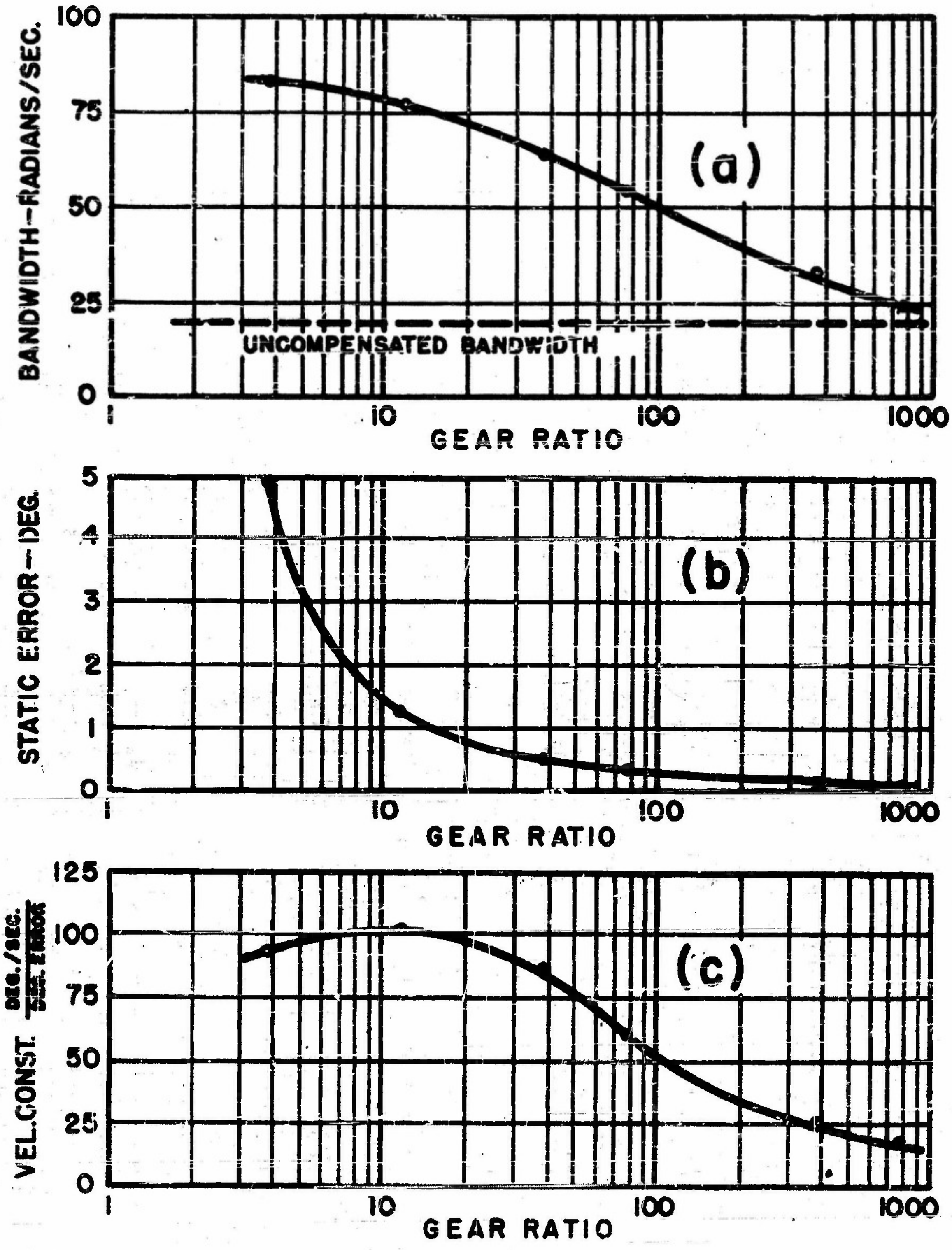


FIG. 19 – SYSTEM PERFORMANCE WITH MARK 8 MOTOR AND NO ADDED INERTIA AND FEEDBACK AROUND TWO STAGES (A SPECIAL CASE OF OPERATION)

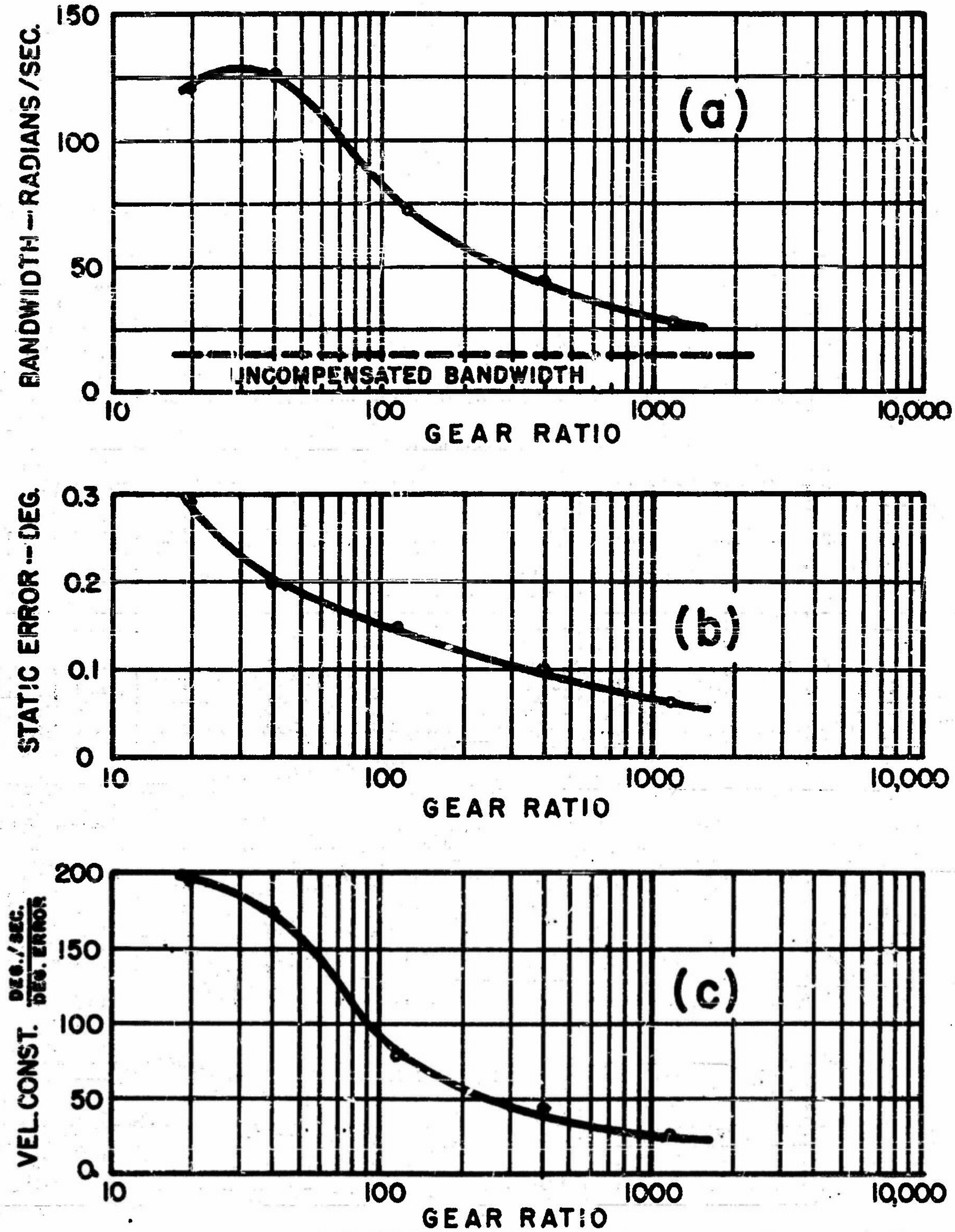


FIG. 20 — SYSTEM PERFORMANCE WITH MARK 16 MOTOR AND NO ADDED INERTIA (TACH NOT USED)

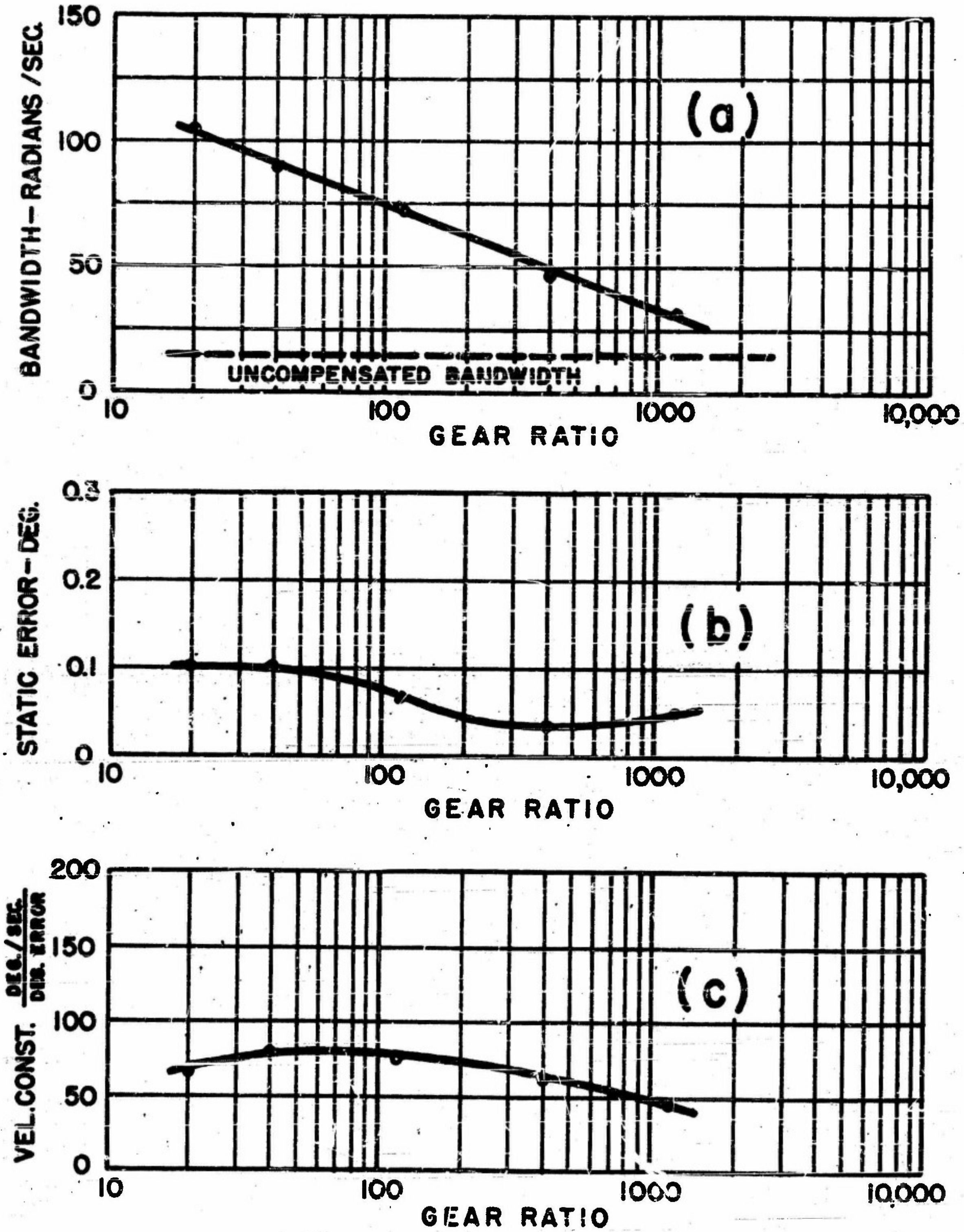


FIG. 21 — SYSTEM PERFORMANCE WITH MARK 16 MOTOR AND NO ADDED INERTIA USING TACH DAMPING

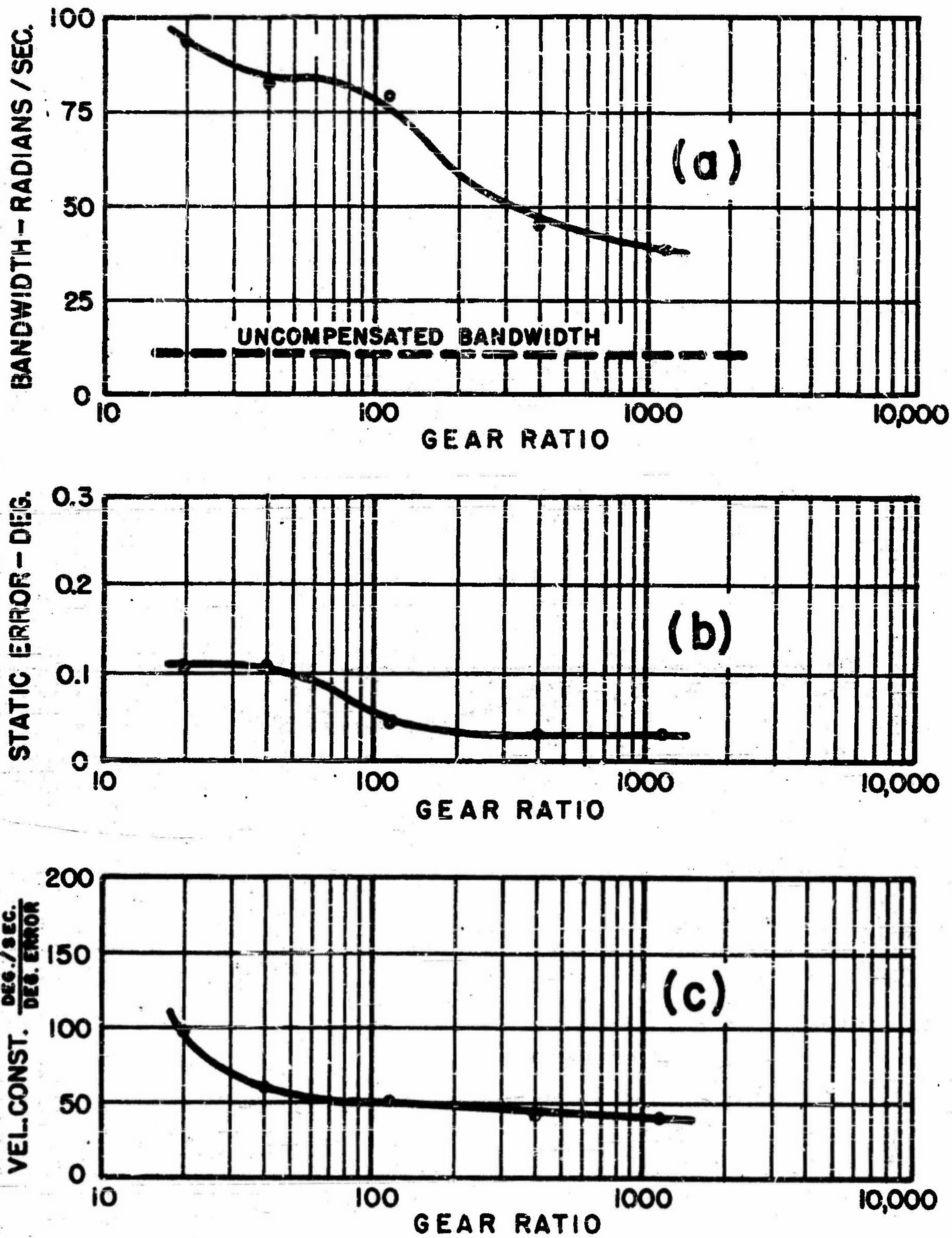


FIG. 22 — SYSTEM PERFORMANCE WITH MARK 16 MOTOR, TACH DAMPING AND TOTAL INERTIA EQUAL 1.41 TIMES MOTOR INERTIA

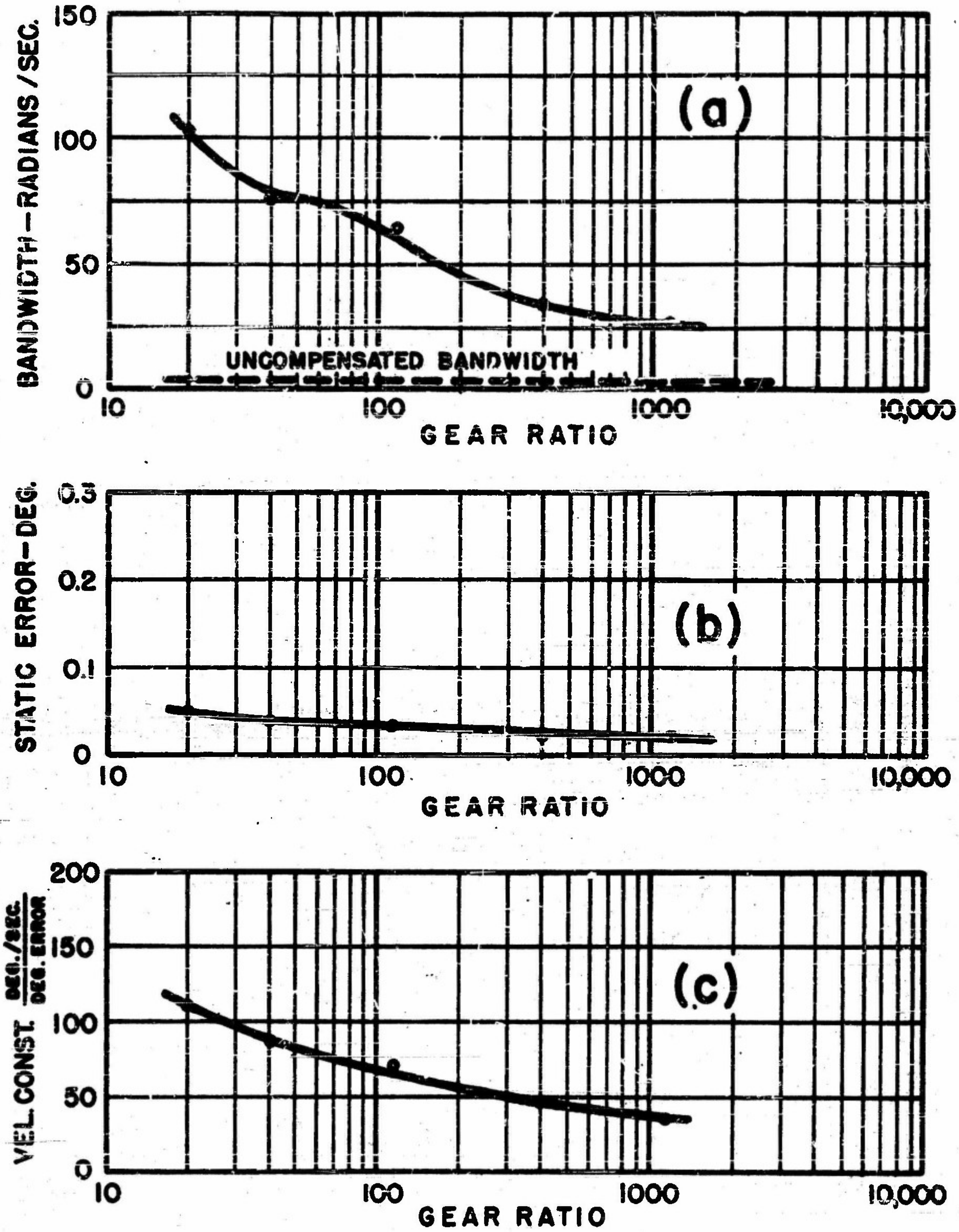


FIG. 23—SYSTEM PERFORMANCE WITH MARK 16 MOTOR, TACH DAMPING AND TOTAL INERTIA EQUAL 3.48 TIMES MOTOR INERTIA

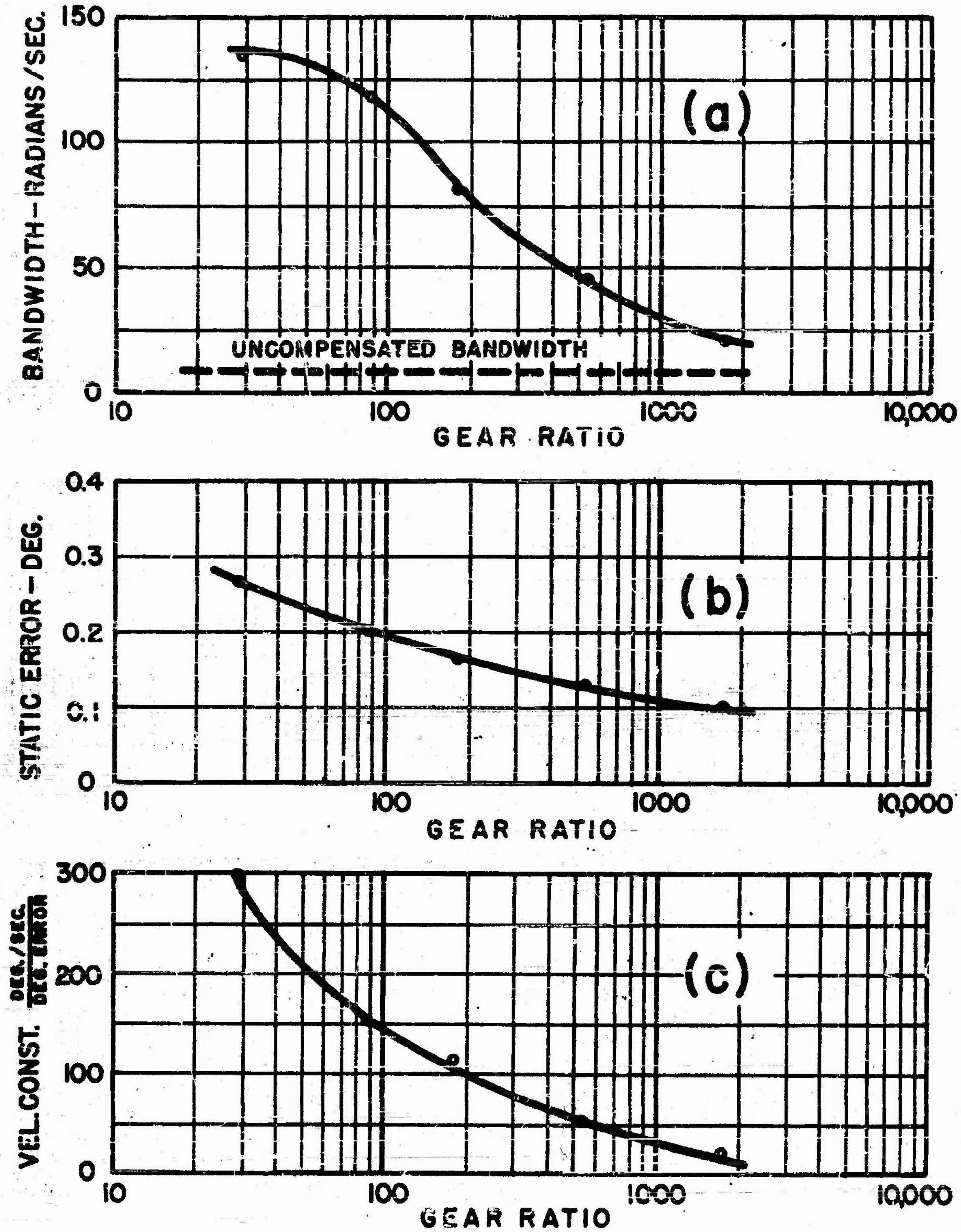


FIG. 24 - SYSTEM PERFORMANCE WITH MARK 14 MOTOR AND NO ADDED INERTIA

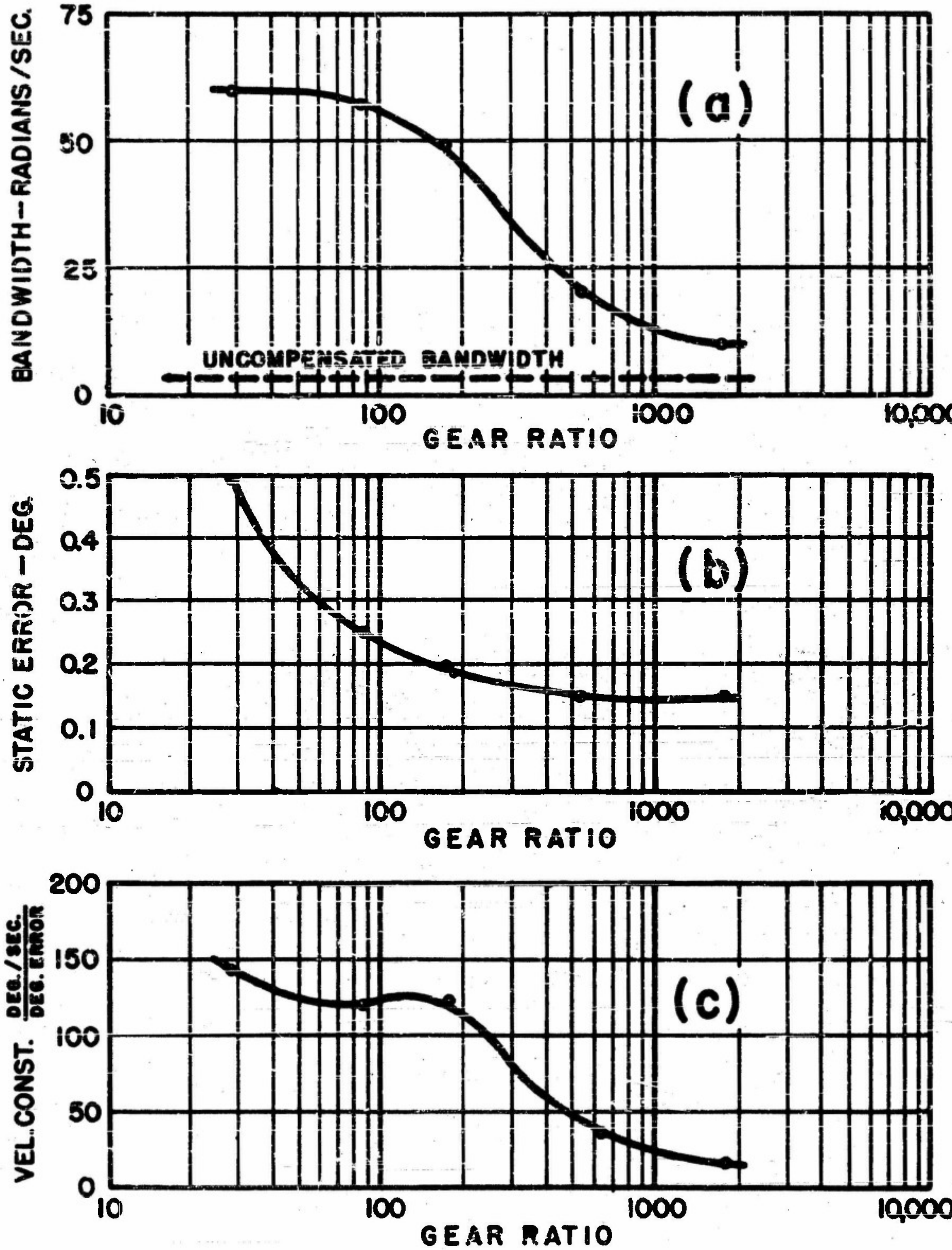


FIG. 25 — SYSTEM PERFORMANCE WITH MARK 14 MOTOR AND TOTAL INERTIA EQUAL 3.0 TIMES MOTOR INERTIA

Table I

VALUES OF COMPONENTS SHOWN IN FIGURE 6 FOR THE MAGNETIC CONTROL AMPLIFIER XM-16A

W1, W4, W7, W10	1250 turns No. 37
W3, W6, W9, W12	1250 turns No. 37 tapped at 800 turns
W2, W5	600 turns No. 37
W8, W11	100 turns No. 37
W13, W16	900 turns No. 30
W15, W18	900 turns No. 30 tapped at 500 turns
W14, W17	100 turns No. 30
RX1, RX2	2 plates, doubler connected, 5/8" sq., Radio Receptor Company
RX3, RX4	6 plates, doubler connected, 5/8" sq., Radio Receptor Company
RX5, RX6	6 plates, doubler connected, 1" sq., Radio Receptor Company
RX7	12 plates, doubler connected, 5/8" sq., Radio Receptor Company
R_a, R_c, R, R_1, R_2	vary with the system used. See Tables III through XV
R_t	used with tach damping. See Tables XI through XIII
R_4	Balance Potentiometer 10K ohms
R_5, R_6	24K ohms, 1 watt*
R_7, R_8	27K ohms, 1 watt*
R_9, R_{10}	18K ohms, 1 watt*
R_{11}, R_{12}	18K ohms, 1/2 watt
R_{13}, R_{14}	30 ohms, 5 watt
R_{15}	5 ohms, 5 watt
C	varies with system used. See Tables III through XV
Pins 1 and 2	115 volts, 400 cycles
Pins 3 and 4	Control signal input
Pins 5 and 6	Amplifier output to motor
Pins 7 and 8	Tachometer feedback input when used

* These values are adjusted to give the proper firing angle for each set of cores.

Table II

VALUES OF COMPONENTS SHOWN IN FIGURE 6 FOR THE MAGNETIC CONTROL AMPLIFIER XM-17A

W1, W4, W7, W10	1250 turns No. 37
W3, W6, W9, W12	1250 turns No. 37 tapped at 800 turns
W2, W5	600 turns No. 37
W8, W11	100 turns No. 37
W13, W16	1250 turns No. 34
W15, W18	1250 turns No. 34 tapped at 800 turns
W14, W17	100 turns No. 35
RX1, RX2	2 plates, doubler connected 5/8" sq., Radio Receptor Company
RX3, RX4, RX5, RX6	6 plates, doubler connected, 5/8" sq., Radio Receptor Company
RX7	12 plates, doubler connected, 5/8" sq., Radio Receptor Company
R_a, R_c, R, R1, R2	vary with the system used. See Tables III through XV
R4	Balance Potentiometer, 10K ohms
R5, R6	27K ohms, 1 watt*
R7, R8	33K ohms, 1 watt*
R9, R10	25K ohms, 1 watt*
R11, R12	18K ohms, 1/2 watt
R13, R14	30 ohms, 5 watt
R15	not used
C	varies with system used. See tables III through XV
Pins 1 and 2	115 volts, 400 cycles
Pins 3 and 4	Control signal input
Pins 5 and 6	Amplifier output to motor
Pins 7 and 8	Not used (the connections shown need not be made)

*These values are adjusted to give the proper firing angle for each set of cores.

Table III

Values of feedback network components for Mark 7 motor with no added inertia
See figure 13 for performance
Total Inertia = J_{m7} ω_1 = 27 Radians/sec.

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec.	ω_2/ω_1
19.25	10K	9K	4µf	6K	4K	800Ω	47.0	1.7
38.5	10K	9K	4µf	6K	4K	260Ω	47.0	1.7
115.5	10K	9K	4µf	6K	4K	60Ω	47.0	1.7
385	10K	16K	4µf	5K	5K	0	38.4	1.4
1155	10K	22K	4µf	9.5K	0.5K	0	36.0	1.3

Table IV

Values of feedback network components for Mark 7 motor with added inertia equal 4.23 times motor inertia
See figure 14 for performance
Total Inertia = 5.23 J_{m7} ω_1 = 5.4 Radians/sec.

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec	ω_2/ω_1
19.25	10K	10K	8µf	5K	5K	280Ω	22.5	4.2
38.5	10K	10K	8µf	5K	5K	150Ω	22.5	4.2
115.5	10K	25K	8µf	3K	7K	70Ω	17.1	3.2
385	10K	25K	8µf	3K	7K	30Ω	17.1	3.2
1155	10K	30K	8µf	4.5K	5.5K	0	16.3	3.0

Table V

Values of feedback network components for Mark 7 motor with added inertia equal 13.3 times motor inertia
See figure 15 for performance
Total Inertia = 14.3 J_{m7} ω_1 = 1.9 Radians/sec.

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec.	ω_2/ω_1
19.25	10K	25K	8µf	2K	8K	260Ω	17.1	9.0
38.5	10K	25K	8µf	2K	8K	100Ω	17.1	9.0
115.5	10K	30K	8µf	3K	7K	50Ω	16.4	8.7
385	10K	40K	8µf	3.5K	6.5K	20Ω	15.5	8.2
1155	10K	40K	8µf	2K	8K	90Ω	15.5	8.2

Table VI

Values of feedback network components for Mark 8 motor with no added inertia
See figure 16 for performance
Total Inertia = J_{m8} ω_1 = 20 Radians/sec.

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec	ω_2/ω_1
19.25	10K	3K	8µf	5K	5K	560Ω	35.1	1.8
38.25	10K	3K	8µf	5K	5K	150Ω	35.1	1.8
115.5	10K	4K	8µf	5K	5K	0	31.3	1.6
385	10K	10K	8µf	7K	3K	0	22.8	1.1
1190	10K	20K	4µf	9.5K	0.5K	0	37.2	1.9

Table VII

Values of feedback network components for Mark 8 motor with added inertia equal 3.03 times motor inertia
See figure 17 for performance
Total Inertia = 4.03 J_{m8} ω_1 = 5 Radians/sec.

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec	ω_2/ω_1
19.25	10K	10K	8µf	3K	7K	280Ω	22.8	4.6
38.5	10K	10K	8µf	3K	7K	110Ω	22.8	4.6
115.5	10K	10K	8µf	3K	7K	0	22.8	4.6
385	10K	15K	8µf	4K	6K	30Ω	19.6	3.9
1155	10K	25K	8µf	5K	5K	0	17.1	3.4

Table VIII

Values of feedback network components for Mark 8 motor with added inertia equal 5.18 times motor inertia
See figure 18 for performance
Total Inertia = 6.18 J_{m8} ω_1 = 3.2 Radians/sec.

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec	ω_2/ω_1
19.25	10K	10K	8µf	4K	6K	260Ω	22.5	7.0
38.5	10K	10K	8µf	4K	6K	120Ω	22.5	7.0
115.5	10K	14K	8µf	4K	6K	50Ω	20.0	6.3
385	10K	20K	8µf	3.5K	6.5K	0	18.2	5.7
1155	10K	20K	8µf	5.5K	4.5K	0	17.9	5.6

Table IX

Values of feedback network components for Mark 8 motor with no added inertia and feedback around two stages
See figure 19 for performance

R_c = 10K
R = 4K
C = 8µf

$R_1 = 0$
$R_2 = \infty$

ω_1 = 20 Radians/sec
ω_2 = 43.8 Radians/sec
ω_2/ω_1 = 2.19

Gear Ratio	Static Accuracy	R_a	
3.85	5.00 deg.	57K	with network
11.85	1.25	22K	" "
38.50	0.50	6K	" "
77	0.30	5K	" "
385	0.10	0.7K	" "
770	0.07	0.5K	" "
2310	0.04	2K	without network
3850	0.02	0.2K	" "

Table X

Values of feedback network components for Mark 16 motor with no added inertia. (Tach not used)
See figure 20 for performance

Total Inertia = J_{m16} ω_1 = 15 Radians/sec

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec	ω_2/ω_1
20	10K	4K	8µf	5K	5K	500Ω	31.7	2.1
40	10K	4K	8µf	5K	5K	130Ω	31.7	2.1
120	10K	4K	8µf	3K	7K	0	33.0	2.1
400	10K	8K	8µf	7.7K	2.3K	0	25.2	1.7
1200	10K	8K	8µf	9.8K	0.2K	0	27.8	1.8

Table XI

Values of components used with Tach damping for the Mark 16 motor with no added inertia
See figure 21 for performance
Total Inertia = J_{m16} ω_1 = 15 Radians/sec

Gear Ratio	R_c	R_a	R_t
20	40K	400Ω	22K
40	20K	300Ω	18K
120	20K	0	45K
400	20K	0	135K
1200	10K	0	50K

Table XII

Values of components used with Tach damping for the Mark 16 motor with added inertia equal 0.41 times motor inertia
See figure 22 for performance
Total Inertia = 1.41 J_{m16} ω_1 = 10.6 Radians/sec

Gear Ratio	R_c	R_a	R_t
20	40K	300Ω	23K
40	20K	200Ω	14K
120	20K	0	44K
400	15K	0	64K
1200	10K	0	15K

Table XIII

Values of components used with Tach damping for the Mark 16 motor with added inertia equal 2.48 times motor inertia
See figure 23 for performance
Total Inertia = 3.48 J_{m16} ω_1 = 4.3 Radians/sec

Gear Ratio	R_c	R_a	R_t
20	17K	0	4K
40	13K	0	3.1K
120	11K	0	4.1K
400	11K	0	11K
1200	10K	0	9K

Table XIV

Values of feedback network components for Mark 14 motor with no added inertia
See figure 24 for performance

Total Inertia = J_{m14} ω_1 = 9 Radians/sec

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec	ω_2/ω_1
28.9	10K	4K	8µf	7K	3K	700Ω	20	2.2
86.6	10K	17K	8µf	0	10K	250Ω	20	2.2
173	10K	17K	8µf	0	10K	120Ω	20	2.2
520	10K	33K	8µf	0	10K	200Ω	16	1.8
1733	10K	33K	8µf	0	10K	50Ω	16	1.8

Table XV

Values of feedback network components for Mark 14 motor with added inertia equal 2 times motor inertia
See figure 25 for performance

Total Inertia = 3 J_{m14} ω_1 = 3 Radians/sec

Gear Ratio	R_c	R	C	R_1	R_2	R_a	ω_2 Rads/sec	$\omega_1/_1$
28.9	30K	10K	8µf	0	10K	400Ω	16.0	5.3
86.6	10K	25K	8µf	0	10K	230Ω	17.0	5.7
173	10K	13K	8µf	1K	9K	0	21.5	7.2
520	10K	15K	8µf	1K	9K	70Ω	19.5	6.5
1733	10K	24K	8µf	1K	9K	60Ω	17.5	5.8

REFERENCES

1. "An Improved Magnetic Servo Amplifier," C. W. Lufcy, A. E. Schmid, P. W. Barnhart, AIEE Technical Paper 52-235, May 1952.

2. "Compensation of a Magnetic Amplifier Servo System," H. H. Woodson, A. E. Schmid, C. V. Thrower, Proceedings of the National Electronics Conference, 1952.

3. Catalogue of Precision Instrument Components, Publication OP 1755, United States Bureau of Ordnance (Washington, D.C.).

4. "Automatic Feedback Control" (book), W. R. Ahrendt, J. F. Taplin, McGraw-Hill Book Company, Inc., New York, N. Y., 1951, page 138.

5. "An Improved Servomechanism Frequency Response Analyzer," Naval Ordnance Laboratory Memorandum 10930, G. B. McCarter.

6. "An Analysis of the Drag-Cup A-C Tachometer by Means of 2-Phase Symmetrical Components," R. H. Frazier, AIEE Transactions, vol. 70, part II, 1951, pages 1890-1906.

DISTRIBUTION

	Copies
Chief, Bureau of Ordnance	
H. B. Rex, Re4-3	2
N. J. Smith, Re4a	2
J. L. Miller, Re8-5	2
W. B. Ensinger, Re8-2	10
A. A. Powell, Re4b	2
Chief, Bureau of Ships	
Code 343	1
J. Watkins, 560E	1
Naval Air Missile Test Center, Point Mugu, California, Attn: Dr. Royal Weller	1
Commanding Officer, U. S. Naval Ordnance Plant, Indianapolis, Indiana, Attn: R. E. Williams, Radar Division	1
Attn: Clare McGillam, Radar Division	1
Senior Naval Liaison Officer, U. S. Navy Electronics Office, Fort Monmouth, New Jersey	1
Director, Navy Electronics Laboratory, San Diego, California, Attn: Robert L. Ogram	1
Commanding General, Wright Air Development Center, Wright-Patterson Air Force Base, Dayton, Ohio, Attn: WCESD-5	1
WCERG-2	1
Mr. R. M. Wundt, WCLGD-2	1
Director, David Taylor Model Basin, Washington 25, D. C. Attn: S. Edward Dawson	1
Director, Naval Research Laboratory, Washington 25, D. C. Attn: John Hart, Electricity Division	1
Rome Air Development Center (RCR), Griffiss Air Force Base, Rome, New York, Attn: Mr. Philip Zirkind, RCRTR-5	1
Commanding General, Frankfort Arsenal, Box 7989, Philadelphia 1, Pennsylvania, Attn: Mr. Donald Brown - FEL	1

Mr. A. E. Schmid, c/o Magnetic Devices, Magnavox Company, Bueter Road, Ft. Wayne, Indiana 1

Mr. C. Krill, c/o Librascope, Inc., 1607 Flower Street, Glendale, California 1

Kearfott Company, Inc., 1150 McBride Avenue, Little Falls, New Jersey, Attn: J. A. Bronson 1

Magnetics, Inc., E. Butler, Pennsylvania, Attn: Mr. E. V. Weir.. 1

RCA Victor Division, Camden, New Jersey, Attn: R. M. Roseman 1

Westinghouse Electric Corporation, 7325 Penn Avenue, Pittsburgh 8, Pennsylvania, Attn: Dr. R. A. Ramey.... 1

Bell Telephone Laboratories, Whippany, New Jersey, Attn: L. W. Stammerjohn 1

Norden Laboratories, Inc., 121 Westmoreland Avenue, White Plains, New York, Attn: Mr. W. J. Brachman 1

Sandia Corporation, Division 1264, Sandia Base, Albuquerque, New Mexico, Attn: Mr. Earl J. Hitt 1

Sandia Corporation, Albuquerque, New Mexico, Attn: Mr. Allen Wooten 1

North American Aviation, Inc., 12214 Lakewood Boulevard, Downey, California, Attn: Dr. Alfred Krausz 1

Wayne Engineering Research Institute, 655 Merrick Avenue, Detroit 2, Michigan, Attn: James R. Walker 1

Regulator Equipment Corp., 55 MacQuesten Parkway South, Mt. Vernon, New York, Attn: W. J. Dornhoefer 1

Ford Instrument Company, 21-10 Thomson Avenue, Long Island City 1, New York, Attn: H. F. McKinney 1

Convair, G.M.D., Computer Group, Pomona, California, Attn: E. V. Mason 1

Convair, Electronics and Guidance Section, San Diego, California, Attn: R. T. Silberman.................... 1

Ahrendt Instrument Company, 4910 Calvert Road, College Park, Maryland, Attn: Mr. W. R. Ahrendt 1

Copies

Massachusetts Institute of Technology, Servomechanisms Laboratory, Bldg. 32, Cambridge 39, Massachusetts, Attn: Professor G. C. Newton, Jr.	1
H. A. Tellman, Technical Liaison Representative, Applied Physics Lab., John Hopkins University, 8621 Georgia Avenue, Silver Spring, Maryland	1
General Electric Company, 1 River Road, Schenectady, New York, Attn: V. J. Louden, Bldg. 28-518	1
W. R. Seegmiller, Bldg. 28, Rm. 518.	1
E. M. Sabbagh, School of Electrical Engineering, Purdue University, Lafayette, Indiana	1
Philco Corp., Philadelphia, Pennsylvania, Attn: R. V. Attarian	1
General Electric Research Laboratories, The Knolls, Schenectady, New York, Attn: H. M. Ogle............	1
Dr. C. S. Hudson, Electrical Engineering Department, Royal Aircraft Establishment, Farmborough, Hants, England	1